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Active Sonar Modelling

With Emphasis on Sonar Stimulators

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Contract Number: W7707-032370/001/HAL

Contract Scientific Authority: Mark G. Hazen (902) 426-3100 x176

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Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2004-130
August 2004

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Abstract

This report summarizes an open-source literature search and survey of the component models required for, and approaches to, active sonar modelling and waveform time-series propagation. Existing sonar stimulator models and facilities are described. Recommendations are made on the maturity and practicality for the subject area of the modelling techniques in reverberation, ambient noise, propagation, environmental models, source models, fluctuation statistics, spatial and temporal coherence, spreading functions and target strength.

Résumé

Ce rapport résume les résultats d'une étude de sources documentaires ouvertes portant sur les modèles composants nécessaires et les approches existantes pour la modélisation de sonars actifs et la propagation de formes d'onde en série chronologique. Des installations et modèles de stimulateurs de sonar actuels sont décrits. Des recommandations sont présentées en ce qui concerne l'exploitabilité et la valeur pratique, pour le domaine d'intérêt visé, des techniques de modélisation de la réverbération, du bruit ambiant, de la propagation, des modèles environnementaux, des modèles de source, des statistiques sur les fluctuations, de la cohérence spatiale et temporelle, des fonctions d'étalement et de l'intensité de cible.

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Executive Summary

Introduction

As part of the Networked Underwater Warfare (NUW) TDP, the Virtual Combat Systems (VCS) group has a requirement to provide active and passive stimulators for the IMPACT airborne and STB ship-borne sonar processors. To support this requirement, an in-depth overview of the current state of active acoustic modeling research is needed in the frequency range 500Hz to 15 kHz for shallow water and bistatic applications.

This report summarizes an open-source literature search and survey of the component models required for, and anproaches to, active sonar modelling and waveform time-series propagation. Existing sonar stimulator models and facilities are described. Recommendations are made on the maturity and practicality for the subject area of the modelling in reverberation, ambient noise, propagation, environmental models, source models, fluctuation statistics, spatial and temporal coherence, spreading functions and target strength.

Results

Component models for active prediction are surveyed. GRAB and PROLOS top the list for propagation model choices.

New developments in component environmental models within the last 10 years include scattering strength theories for sediment roughness, sediment volume inhomogeneities, and surface wave bubble cloud scatter. A new formulation of ray theory has been applied to layered bottom propagation and the temporal spreading produced in the time series is striking. Finally, new data confirm the statistical distributions of sediment reverberation are significantly non-Gaussian.

Component model shortcomings include the lack of a seamless bottom loss across the entire frequency range (currently there are three separate models to transition), the lack of target strength models for the upper end of the frequency range, and the lack of input information to supply the newest sediment models.

Stimulation facilities are surveyed and, as one might expect, they are all hardware oriented and invest their acoustic resources primarily on target modelling.

Existing stimulator models are surveyed and they all seem designed to perform at mid to high frequency or in deep water because they all employ conventional ray theory for their propagation calculations. The leading candidate stimulation model is SST because of its versatility and availability, however it is presently designed for high frequency applications.

Some capabilities common among stimulation models are the offering of a full range of beam patterns and pulse types, the ability to include range dependence in bathymetry, and the capability to handle bistatic geometries.

Some deficiencies common among stimulator models are the use of older scattering strength models, the neglect of the temporal structure of bottom layering reflections, and the application of Gaussian statistics for all fluctuations. All these deficiencies can be traced directly to the lack of input information to support the newest models and statistical

distributions. To address these deficiencies, all of the stimulation models permit user-supplied tables as inputs.

Active propagation and system performance models are surveyed and the model deemed most adaptable to the construction of a stimulation model is CASS due to its extensive documentation and broad choice of components and capabilities. It has wide usage among the Naval community and is currently employed in two of the existing stimulator models. However, CASS uses a ray model for propagation and therefore is not the best choice for shallow water, low frequency application. For these environments, SWAMI is recommended.

Significance

There do not appear to be any existing models that would fully satisfy the requirements for computing time series for shallow water, low frequency operation as well as for 15,000 Hz applications. However, the leading candidate stimulator, SST could be combined with the propagation model PROLOS to broaden its capabilities beyond ray theory for ducted and boundary-limited propagation.

The most important physical effects that are not currently modelled adequately in any of the models surveyed are the fluctuation statistics of bottom reverberation and temporal spread functions from bottom penetration. Both of these effects are crucial to accurately describe the pulse distortion and masking in a shallow water bottom limited environment.

The results of this survey indicate that obtaining a COTS solution that adequately addresses the requirements for realistic active and passive signal generation in shallow water environments is unlikely.

Future Work

This report provides a first step in quantifying a move in DRDC Atlantic's acoustic modelling and simulation from performance prediction to acoustic system stimulators. The key requirement is for believability at the operator display, and therefore the inclusion of realistic fluctuation statistics for shallow-water scenarios will need to be addressed. The SST stimulator will be evaluated further to determine if it can be effectively extended to lower frequencies.

McCammon, D.F. 2004 Active Sonar Modelling with emphasis on sonar stimulators DRDC Atlantic CR 2004-130. Defence R&D Canada – Atlantic

Sommaire

Introduction

Dans le cadre du PDT sur la guerre sous-marine en réseau (GSMR), le groupe des systèmes de combat virtuel (SCV) a besoin de stimulateurs actifs et passifs pour les processeurs de sonar aéroportés du banc d'essai multistatique intégré actif/passif (IMPACT) et les processeurs de sonar embarqués du banc d'essai de systèmes (STB). Pour répondre à ce besoin, il est nécessaire d'effectuer un examen d'ensemble approfondi de l'état des recherches en modélisation acoustique de systèmes actifs pour les applications bistatiques et fonctionnant en eaux peu profondes dans la gamme de fréquences de 500 Hz à 15 kHz.

Le rapport résume les résultats d'une étude de sources documentaires ouvertes portant sur les modèles composants nécessaires et les approches existantes pour la modélisation de sonars actifs et la propagation de formes d'onde en série chronologique. Des installations et modèles de stimulateurs de sonar actuels sont décrits. Des recommandations sont présentées en ce qui concerne l'exploitabilité et la valeur pratique, pour le domaine d'intérêt visé, des techniques de modélisation de la réverbération, du bruit ambiant, de la propagation, des modèles environnementaux, des modèles de source, des statistiques sur les fluctuations, de la cohérence spatiale et temporelle, des fonctions d'étalement et de l'intensité de cible.

Résultats

Le rapport étudie des modèles composants de prévision active. Le modèle pour les faisceaux de rayons gaussiens (GRAB) et le modèle pour mode normal (PROLOS) dominent la liste des choix de modèles de propagation.

Les progrès réalisés dans le développement de modèles environnementaux composants depuis 10 ans comprennent l'élaboration de théories sur l'indice de diffusion applicables à la rugosité des sédiments, aux inhomogénéités volumiques des sédiments et au clutter de nuées de bulles des vagues de surface. Une nouvelle formulation de la théorie des rayons a été appliquée à la propagation sur fond multicouches, et l'étalement temporel produit en série chronologique est frappant. Enfin, de nouvelles données confirment que les distributions statistiques de la réverbération sur les sédiments sont sensiblement non gaussiennes.

Les lacunes du modèle composant comprennent l'absence de perte au fond sans coupure dans l'ensemble de la gamme de fréquences (il y a actuellement trois modèles distincts pour la transition), l'absence de modèles d'intensité de cible pour la partie supérieure de la gamme de fréquences et l'absence de données d'entrée pour les plus récents modèles de sédiments.

Des installations de stimulation sont étudiées et, comme on pouvait s'y attendre, elles sont toutes orientées matériel et utilisent leurs ressources acoustiques principalement pour la modélisation de cibles.

Des modèles de stimulateurs existants sont étudiés et ils semblent tous conçus pour fonctionner dans la gamme allant des fréquences moyennes aux hautes fréquences, ou en eaux profondes, car ils se fondent tous sur la théorie classique des rayons pour leurs calculs de propagation. Le Sonar Simulation Toolset (SST) est le principal modèle candidat en

raison de sa polyvalence et de sa disponibilité, mais il est actuellement conçu pour des applications hautes fréquences.

Les modèles de stimulation ont en commun certaines capacités; ils offrent tous une gamme complète de diagrammes de rayonnement et de types d'impulsions, la capacité d'inclure la dépendance en distance en bathymétrie et la capacité d'utiliser les géométries bistatiques.

Les modèles de stimulation ont aussi en commun certains défauts comme l'utilisation d'anciens modèles d'indice de diffusion, la négligence de la structure temporelle des réflexions sur le fond multicouches, et l'application de statistiques gaussiennes à toutes les fluctuations. Tous ces défauts peuvent être attribués directement à l'absence de données d'entrée pour les plus récents modèles et distributions statistiques. Pour tenir compte de ces défauts, tous les modèles de stimulation permettent l'entrée de tables définies par l'utilisateur.

Des modèles de propagation active et de performance des systèmes sont étudiés et le modèle jugé le plus adaptable à la construction d'un modèle de stimulation est le Comprehensive Acoustic System Simulation (CASS) en raison de la documentation extensive et du vaste choix de composants et de capacités qu'il offre. Il est largement utilisé dans le milieu naval et est actuellement appliqué dans deux des modèles de stimulateurs existants. Toutefois, comme le CASS utilise un modèle de rayons conçu pour la propagation, il n'est pas le meilleur choix pour les applications à basses fréquences en eaux peu profondes. Dans ces milieux, l'initiative de modélisation de sonar actif en eau peu profonde (SWAMI) est recommandée.

Portée

Il ne semble pas exister de modèles satisfaisant entièrement aux exigences du calcul de séries chronologiques pour les opérations basses fréquences en eaux peu profondes et les applications à 15 000 Hz. Toutefois, le principal stimulateur envisagé, le SST, pourrait être combiné au modèle de propagation PROLOS afin d'étendre ses capacités au-delà de la théorie des rayons applicable à la propagation dans des conduits et à l'intérieur de limites.

Les effets physiques les plus importants qui ne sont actuellement modélisés de façon satisfaisante dans aucun des modèles étudiés sont les statistiques de fluctuation de la réverbération sur le fond et les fonctions d'étalement temporel associées à la pénétration du fond. Ces deux effets sont d'une importance cruciale pour la description exacte de la déformation des impulsions et le masquage dans un milieu d'eaux peu profondes limité par le fond.

Les résultats de l'étude indiquent qu'il est peu probable qu'on trouve une solution commerciale courante qui réponde de manière satisfaisante aux exigences de la génération réaliste de signaux actifs et passifs dans des milieux d'eaux peu profondes.

Recherches futures

Le présent rapport marque une première étape de la quantification du passage, à RDDC Atlantique, de la modélisation/simulation acoustique fondées sur des prévisions de performance, à des stimulateurs de systèmes acoustiques. La principale exigence vise à assurer la vraisemblance de l'affichage opérateur. À cet égard, des travaux devront porter sur l'inclusion de statistiques de fluctuation réalistes pour des scénarios en eaux peu profondes. Le stimulateur SST sera en outre évalué afin de déterminer si son application peut être étendue efficacement à des fréquences plus basses.

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1. Introduction

1.1 Purpose and Scope

As part of the Networked Underwater Warfare (NUW) TDP, the Virtual Combat Systems (VCS) group has a requirement to provide active and passive stimulators for the IMPACT airborne and STB ship-borne sonar processors. The stimulators will be driven by the output of a common maritime virtual environment under development known as the Common Ocean Virtual Environment (COVE). As well, there are a variety of other projects, including Rapid Environmental Assessment (REA), that require varying fidelities of active modelling. An informal project team is being formed to investigate and develop the active acoustic portion of COVE to support REA using reverberation and the requirements for the stimulators. In preparation for this work, the team requires an in depth overview of the current state of active acoustic modelling research.

The purpose of this report is to review the open literature and compile an overview of models and approaches for active sonar modelling and time series propagation for stimulation purposes in the frequency range from 500Hz (3 m wavelength) to 15 kHz (10 cm wavelength). A sonar stimulator is herein defined as a computer system that produces artificial signals that are indistinguishable in some application-dependent sense from that which would be detected by real sonar system hardware. This artificial signal combines four types of sources: discrete sound sources (radiated noise from ships or countermeasures), diffuse sound sources (environmental noise and self-noise), discrete scatterers (targets or false targets that produce echoes), and diffuse scatterers (reverberation from all boundaries and the water column). This review attempts to span all these contributors by surveying models of reverberation, ambient noise, propagation, the environment, source waveforms, fluctuation statistics, and target models.

This report is organized to present the newest models and theories applicable to active modelling targeted to the frequency range of interest. Section 2 discusses propagation modelling and lists some specific models suitable for active calculations over the entire frequency range required. Section 3 covers reverberation models. Section 4 discusses environmental models. It reviews a host of scattering theories for surface, bottom and volume. It also discusses fluctuation statistics, coherence, spreading functions and ambient noise. Section 5 covers source and target models while Section 6 discusses time series generation. Existing stimulation facilities and software are covered in Section 7. Also included are the results of a questionnaire sent out to the stimulator developers. An extended bibliography provides additional reading. Paul Etter[1] has been collecting and compiling acoustic models for many years. In 2003, he published a book on the topic that is particularly useful for this task, because it contains a comprehensive review of developments in acoustic modelling and is a rich source of model names, descriptions and references.

2. Propagation Modelling

2.1 Types of Models

The mathematical modelling of sound propagation in the ocean is a popular topic for many researchers. Generally, the best of these models fall into four categories according to the physics and mathematics being employed. These categories are: Ray theory, Normal Mode theory, Greens Function expansions, and Parabolic Equations.

2.1.1 Range Dependence

Of these classes of models, Ray theory and the Parabolic Equation are best suited to handle range dependence in bathymetry and sound speed profiles. There is an extension for Normal Mode theory called the adiabatic approximation that gives it weak range dependence. In Etter[1], table 4.1, there are 114 underwater acoustic propagation models listed, 80 of which are range dependent.

2.1.2 Active Propagation

Of these classes of models, Ray theory is best suited to active modeling because it can easily form the in-coming and out-going fields required for modelling boundary reverberation and scattering and because it can distribute its rays in time. The Parabolic Equation is generally thought to be unsuitable because it computes only the forward going field and has no temporal differentiation, however a new two-way PE is reviewed below. Normal Mode theory, strictly speaking, does not make temporal differentiation or compute scattered field components. However, a technique can be used whereby the modal energy is decomposed into up-going and down-going components analogous to rays. In its simplest form, this technique is called multipath expansion. Closed form modal depth functions of sinusoids or Airy Functions are best suited for this decomposition.

Another normal mode approach that has been applied to pulse propagation is the Pekeris waveguide, extended to include a sediment layer by Bothell[2]. The solution technique uses Airy functions for eigenfunctions, modal group velocities for temporal structure, and the method of stationary phase to estimate the inverse Fourier transform for the time series. The limitations are the use of isovelocity water and the difficulty of finding modes by the solution of a transcendental equation. This method has been extended to allow a variable water column in the models HELFIRE (NAWC) and ORCA (ARL/UT), however both these models have only weak range dependence.

In 2002, Chris Tindle[3] published a new technique for pulse propagation. It represents a hybrid mode/ray approach using the WKB approximation on the Hankel transform solution to the wave equation. This new ray theory is valid at relatively low frequencies and the phase, amplitude and travel time of broadband acoustic pulses are obtainable directly from a simple graph of ray travel time as a function of depth at a given range. Tindle describes the method as fast and in close agreement with normal-mode calculations, and he states that the method can handle range dependence.

In Etter[1], table 10.6, there are 26 active sonar performance models listed, all of which are multipath expansion based or ray based models. The current U.S. Navy standards

designated by the Oceanic and Atmospheric Master Library, U.S. Naval Oceanographic Office, (OAML) for active modelling are ASTRAL from 50 Hz to 5000 Hz, and GRAB from 10 kHz to 100 kHz, as of January 1999. Application has been made to OAML to extend the lower frequency limit of GRAB down to 500 Hz.

2.1.3 Shallow Water Applications

Most of the difficulties in shallow water modeling are associated with the extreme variability. The bottom type and sound speed profile are inherently more variable than those in deep water. The bottom sediments are different in character than those in deep water. They are generally deep layers of sands and muds that support a host of biological life, while deep water sediments are often ooze overlying bedrock. Shallow water sediments have a large range of roughness size distributions because of the shells, sand waves, and trash that litters the bottom. There is more marine life, often making the volume scattering strength in reverberation larger than the surface or bottom contribution. There is more shipping activity making the ambient noise higher and putting more transient spikes into the noise field. The best model type for shallow water is acknowledged to be Normal Mode theory, both because it handles complex bottom penetration and because it correctly describes the sound field in narrow confides (shallow water is really a duct propagation problem). Mode theory is also more efficient in shallow water than Ray theory, because the number of modes is much fewer than the number of eigenrays. However, its weak range dependence is a disadvantage in the variable environment.

In 2004, there was a short note by Michael Ainslie[4] that may have some application to the shallow water propagation problem. He shows that the correct formulation of propagation loss should include the ratio of characteristic impedances ($\rho_r c_r / \rho_s c_s$) at source and receiver locations, and since the conditions in shallow water are so variable, this factor may become more important than in deep water where it is often neglected.

2.1.4 General Model Weaknesses

Each class of models has its weaknesses. Ray theory is weakest at low frequencies where bottom losses cannot be accurately specified by simple plane wave reflection coefficients, particularly at frequencies below 200 Hz where shear waves are important or where significant bottom penetration and reradiation is occurring. Normal Mode theory is weakest in strongly range dependent environments and it becomes slower as frequency or water depth increases. Under the multipath expansion technique, the decomposition of modes into ray-like components requires the same reflection coefficients as ray theory, and hence suffers from the same low frequency weakness. Green's functions expansions are very time intensive, and have generally only been used as benchmark models. The Parabolic Equation is extremely slow at frequencies above 1000 Hz and is not generally able to model active propagation. Choosing the best model for a particular application often requires identifying the model whose weaknesses are the least intrusive.

2.2 Specific Propagation Models Suitable for Active Calculations

Some specific propagation models suitable for active calculations in the frequency range 500Hz to 15000 Hz are discussed below.

2.2.1 PROLOS

PROLOS is a normal mode model written by Dale Ellis[5] in 1995 specifically for active applications in shallow water. Ellis writes, "Since the shallow-water transmission problem is well described in terms of normal modes, it is natural to look for a solution to the reverberation problem in terms of normal modes. There are two difficulties: how to include the time dependence and how to handle the scattering. The first problem arises because the wave models are single-frequency, continuous-wave (CW) models, so in principle a Fourier synthesis is required to handle the time dependence of the pulse. The second problem arises because much of scattering theory is formulated in terms of incident plane waves, so at every range it is necessary to decompose the acoustic field into its incident and reflected components." The solution to including time dependence used in PROLOS is to compute the travel time of each mode based on its modal group velocity. The requirement for plane waves at the scattering interface is met by decomposing the mode into up-going and down-going sinusoidal waves with reflection coefficients.

The strength of mode theory for shallow water is that it is efficient and accurate at low frequencies. Unfortunately, the very mechanism that makes the PROLOS approach suitable for reverberation (decomposition of field into ray-like terms) is also a weakness because the use of reflection coefficients for bottom losses becomes questionable at low frequencies where there is significant sediment penetration. Extensions to the theory used in PROLOS were published in 1999 by LePage[6], in which the temporal characteristics of modal interaction with the seafloor were included in order to predict the extent of coherence of the backscattered field.

At higher frequencies, the number of modes may become excessive. In 1999, Terry Deveau[7] presented a method for achieving efficiency when a large number of modes are propagating. The method progressively omits the time-intensive numerical solution of each mode by sampling a small fraction of them and reconstituting the missing modes during the final calculations by interpolation. Since the number of modes is proportional to the product of the frequency and water depth, this method represents an extension of the use of PROLOS to deep water and/or higher frequencies.

Another weakness of the PROLOS model is that it employs an adiabatic range-dependence. This consists of range-averaging the eigenvalues of each mode, and the technique is only valid for small changes in bathymetry or sound speed profile with range. It also makes the code more labour-intensive as it has to re-compute the mode functions at each range change.

2.2.2 GRAB

GRAB (Gaussian Ray Bundle)[8] is a ray theoretical model introduced in 1996 that allows the rays to have a "width", that is, a Gaussian spread of energy in depth about the central ray path. Using this type of expansion, one need not use shooting techniques to connect every ray from source to receiver as conventional ray models do, because the spread of the ray ensures that every ray intersects the receiver location at some point on its vertical distribution. However, the number of rays being computed is large because the spacing of eigenrays calls for vertical angle increments of 0.1° or even 0.01°, therefore this model is not particularly fast. Being a ray model, it is capable of handling any range dependence in bathymetry, bottom loss and sound speed profile.

The most citied weakness of this models' mathematics is the lack of rigor in the specification of the width of the Gaussian rays, determined empirically to have a minimum aperture of $4\pi\lambda$. If this lower bound were in error, it would show up primarily in shadow zone computation, but GRAB seems to be entirely accurate there, so I don't feel this criticism is important. The GRAB model has been tested against the benchmark EFEPE parabolic model at frequencies as low as 25 Hz in deep water and 1000 Hz in shallow water, and I am impressed with the ability of GRAB to reproduce the coherent phase oscillations of the low frequency field.

2.2.3 Two-way PE

In 1992, Collins and Evans[9] developed a two-way parabolic equation for modelling backscattering. In this technique, they approximated range dependent bathymetry as a sequence of range-independent regions. Interface conditions were then matched across the vertical boundaries between regions using a parabolic approximation for the range derivative. The major weakness of this approach for application in the frequency range 500 Hz to 15 kHz is that of speed, since the PE becomes very time-intensive as the frequency increases and it is seldom used above 1000 Hz.

In 1996, Kevin Smith and Fred Tappert[10] also used a parabolic equation (UMPE- a broadband version) to analyze reverberation from the Mid-Atlantic ridge experiment. They were trying to correlate high returns with bathymetric features, and used a quazi-ray trace to obtain travel times. The frequency of the experiment was 200-255 Hz. The reason the parabolic approximation worked here is that they were mapping long-range scattering, which occurs at low angles. The PE is not very accurate for short-range high angle propagation.

There is a very detailed review of the many PE models and approaches in Lee, Pierce and Shang[11]. While they don't explicitly list reverberation and active modelling as an accomplishment, these two examples shown above prove that one can successfully use the parabolic equation to predict reverberation in a few limited circumstances.

2.2.4 ASTRAL

The ASTRAL model is a type of multipath expansion model being currently used as an active propagation prediction tacaid. It is designed to estimate the power level of the propagated field in an ultra-fast way for fleet applications that require lightning speed. It has very limited application to coherent sound field computation because the phases of its "smodes" (smeared modes) are only crudely approximated.

2.2.5 Active Raymode

Active Raymode is a multipath expansion model similar in function to ASTRAL. While it computes its phases with a bit more care than ASTRAL, it has eliminated the coherent field from its output products and it cannot handle range dependence.

2.2.6 MOCASSIN

The ray theoretical model MOCASSIN (Monte Carlo Sound Ray Intensities)[12] was developed in 1990 for active sonar in shallow water with highly variable sound speed conditions and poor knowledge of input data. It can accommodate a range-dependent bathymetry and bottom loss but not sound speed profile *per se*. To account for sound speed

variability, the model assumes a Gaussian distribution of ray angles caused by the random component in the sound speed. The variance of the distribution is governed by the sum of the product of the speed diffusion constant and the path length in each layer, the diffusion constant being user chosen. As the path length changes with a range-dependent bathymetry, the width of the ray bundle will change, simulating in some sense a range-dependent profile. To account for the frequency dependence of ducted propagation, the authors smooth (low pass) the sound speed profile by a running average 7 wavelengths long. The filter eliminates sound channels smaller than this and large gradients are smoothed, which the authors claim will simulate diffraction. The 7λ cut-off must have been selected based on experience because theoretically duct cut-off occurs at λ/4. There is no smoothing done at frequencies above 5 kHz. The program computes the incoherent average of intensity in a vertical receiver window. Then it range averages internally and stores the field versus depth and range for post processing of receiver beams, depths and target ranges.

2.3 Opinions on Propagation Models

Not-recommended

Two-Way PE is not a good choice because it would be inordinately slow at the upper end of the frequency bandwidth and because this particular model does not have any track record among other users. ASTRAL is not a good choice because its mathematics are too approximate and its intensity has only rudimentary coherence in convergence zones. Active Raymode is not a good choice because it has no range dependence, and with the death of its creator and the loss of Navy Standard status in OAML, I'm not even sure its being supported any more. I can't recommend the use of MOCASSIN because I have not found any published data comparisons and I do not know how much the sound speed filtering will affect low-frequency ducting. The important input diffusion constant can only be guessed at. The output format (range- averaged incoherent intensity) will not be useful at constructing time series because it lacks phase information.

Provisionally Recommended

While PROLOS has a good reputation, after consideration of the frequency range to be spanned and the desire to include steep slopes and canyons in bathymetry, I can't recommend PROLOS to cover all applications. Its range dependence is too weak and it would be very slow at the high end of the frequency range. It could be offered as an alternative choice for propagation under special circumstances of shallow water and complex sediments. Having the developer in house is a real plus.

Another model that should be examined for provisional recommendation is that of Chris Tindle[3]. I have personally seen him demonstrate the capability of his new ray/mode approach and I think there it has a lot of potential for accurate pulse propagation. I do not think he has named his model, and it may not mature enough yet for general use, but I think it should be investigated further.

Recommended

Any of the high fidelity ray theory models would be appropriate. The current favourite of the U.S. Navy, GRAB seems to be robust in deep or shallow water and it would cover the frequency range comfortably. The OAML Navy Standard designation has resulted in the production of extensive documentation on GRAB and a lot of IV&V model testing had been performed by non-developers- who are the first people to 'break' a model. It is currently being

employed in a wide variety of Navy applications and it has developed a good reputation. It is not fast, but the speed is independent of frequency, depending only on the ray sampling density. The comparison with 1000 Hz benchmark EFEPE predictions were very good, showing that GRAB is handling coherence correctly. I feel this model would be suitable for building a stimulator. The developers, Ruth Keenan and Chic Weinburg, are friendly and sincerely want to see people be successful with their model, so they would likely help if needed.

Note

Both PROLOS and GRAB require bottom reflection coefficients. For applications in which we wish to reproduce the observed signal in areas where we have knowledge of the bottom character, it is imperative that we use a good reflection coefficient model (employing layering and elastic propagation if possible) rather than relying on the LFBL bottom loss province and LFBLTAB conversion or the HFBL (MGS) province losses.

One weakness of these two models is that since both models use plane wave reflection coefficients rather than tracing rays or decomposing modes within the sediment, the temporal distribution of the sub-bottom reflections is not computed (see the bottom layering discussion in Section 4.8.5). The LePage derivations for PROLOS would appear to correct this omission and should definitely be investigated.

3. Reverberation Modelling

3.1 Reverberation Theory

A generalized equation for the bistatic reverberation intensity due to boundary scattering can be written as

$$R(t) = \iint_{A(t)} \sum_{i} \sum_{r} I_0(t - t_i - t_r)\, P_i(\theta_i)\, P_r(\theta_r)\, S(\theta_i, \theta_s, \varphi)\, dA$$

Subscripts t and r refer to source and receiver. I_0 is the intensity of the source, dA is the elemental scattering area connected by the propagation terms P. The scattering strength is S. The double sum counts all rays (or modes) associated with each propagation expression P. The double integral covers all areas touched by the pulse from each source and receiver footprint. All angles have implicit time dependence, and the angles at source and receiver (t and r) are not the same as the angles at the scattering surface (i and s) due to water column refraction. In this most general expression, the scattering strength equation can be a complicated function of the angles and slopes of the scattering surface. All of the high fidelity reverberation models follow these mathematics, however each model chooses different methods for evaluating the propagation field, the scattering function, and in some cases, the scattering area.

A highly recommended detailed review of methods and issues related to the simulation of ocean reverberation was given by Goddard[13] (the creator of SST) in 1993. In this paper, Goddard derives the mathematics of two reverberation methods, the point scatterer method and the scattering function method, and discusses the appropriate usage of each.

In 1999, a Shallow-Water Reverberation Focus Workshop[14] was held in Santa Fe, New Mexico, sponsored by the Office of Naval Research (ONR). The objective of this workshop was to identify current issues related to shallow-water reverberation, scattering mechanisms and associated reverberation experiments. The key focus was on bottom reverberation and bottom scattering in the frequency range from 50 to 6000 Hz. The workshop participants agreed on the following definitions:

- Reverberation: Any source related energy received by an acoustic sensor after signal generation ons3et that is not energy returned by a target (and in the bistatic case, not the one-way received energy associated with a transmission loss measurement from source to receiver). This definition excludes ambient/background noise. The group consensus was to sidestep the issue of separately treating forward scatter as it relates to reverberation.
- Clutter: That which comes though a sonar display that can be confused with a target or confound the classification process. The definition therefore is dependent on the sonar system being used.
- Bottom Scattering: The very localized process of redirecting incident energy from a confined bottom or sub-bottom patch. It does not include the specularly reflected portion of the redirected energy.

Table 1. *Reverberation Models from Preston[14], Appendix B].*

PHYSICAL APPROACH	MODEL NAME	CREATOR AND LAB
Ray Based	GSM	Weinberg NUWC
	BiRASP	Fromm NRL
	CASS/GRAB	Weinberg NUWC
	China models	Wu
Wave Based plus Separable Scattering	BIKR	Fromm NRL
	UMPE-Reverb	Tappert Univ. of Miami Smith NPS
	OGOPOGO, SWAMI	Ellis DRDC Atlantic
	PAREQ-Reverb	Schneider, Jensen FWG, SACLANTCEN
Two-Way Wave Based Multiple Scatter	COUPLE	Evans SAIC, Odom APL/UW, Knobles ARL/UT
	Integral Equation Based	Thorsos et al APL/UW Fawcett DRDC Atlantic
	FFP based model	Makris MIT
	T-Matrix broadband	Tang APL/UW
Numerical Two-Way Wave Based	OASES	Schmidt MIT
	FINDIF	Stevens WHOI
	Pseudo spectral approach	Turgut NRL
	FOAM, SAFE	Chin Bing NRL

Preston[14] gives a detailed discussion of the recommendations and questions that resulted from this workshop. He has also compiled a list of reverberation models that are repeated in Table 1. Most of these models are concerned with reproducing measured reverberation from known sediment properties and measurement system configurations. They are highly detailed and complex since they must include high fidelity propagation as well as scattering. Several of the potentially useful reverberation models are discussed in more depth below.

3.2 Specific Reverberation Models Suitable for 500-15,000 Hz Operation

3.2.1 OGOPOGO

OGOPOGO was created by Dale Ellis[5] in 1995 to model shallow water reverberation. The propagation engine for this model is PROLOS. There is a short discussion of the use of normal modes for boundary and volume reverberation and target echo calculations in the Oceans '97 Proceedings[15]. The OGOPOGO model has been successfully compared to some shallow water data in Desharnais and Ellis[16].

3.2.2 BiRASP

BiRASP, the Bistatic Range-dependent Active System Performance prediction model was created in 1996 by David Fromm.[17] It predicts long-range low-frequency boundary reverberation and target returns. It allows arbitrary source/receiver configurations with Nx2D range and azimuthal dependence in all environmental parameters. It computes propagation loss with GRASS, a ray theoretic algorithm developed in 1968. It uses Lambert's Law with the Ellis bistatic bottom scattering model for bottom backscattering strength and the Ogden-Erskine surface backscattering strength model. Its output products include transmission loss, target echo and signal excess with optional time-angle spreading.

3.2.3 CASS

Comprehensive Acoustic System Simulation (CASS) contains capabilities that make it a much broader simulation than just reverberation modeling, and so it is described more fully under the other active models in Section 7.4.3. It contains several propagation models, however the most frequently used one is GRAB; hence the model is often referred to as CASS/GRAB.

With regard to the reverberation computations in CASS, Ruth Keenan[18] has given a short description of the logic in the computation. CASS employs a 7-nested do-loop. The inner loop collects all the reverberation contributions over the user-requested sampling times. There are two loops on eigenray paths, one for the paths connecting the transmitter to the scattering cell and the other for the paths connecting the scattering cell to the receiver. Since the reverberation is calculated in the time domain and there may be contributions in the same time bin from different ranges, the next loop increments the range. The remaining 3-nested do-loops simply repeat this process for each bearing angle, frequency and receiver steering angle. The inner bearing angle loop is typically used to sample the horizontal beam pattern of a towed array. If the user specifies a beam pattern with a fixed horizontal beam width then this loop is unnecessary. The final outer loop is also over bearing angle but in this case the

receiver is now steered in the new bearing angle direction and will use the appropriate range dependent eigenray files for the new direction.

3.2.4 Opinions on Reverberation Models

All three of these models are of high enough quality that their reverberation models are well founded, and they could all be recommended. OGOPOGO and CASS have an edge over BiRASP because the former have high fidelity propagation models, while BiRASP uses an old style ray trace GRASS. Remember that it is important for self-consistency to select the same propagation loss algorithm as is employed in the reverberation calculation. That insures that the same sampling representation and fidelity assumptions would be obtained for all parts of the received signal; direct blast, fathometer returns and reverberation.

4. Environmental Models

All propagation or reverberation models must have sub-models and inputs describing the environmental effects on the sound. This section begins with a review of scattering theory then discusses several of the most recently developed theories on bottom and surface scattering.

4.1 Review Of Scattering Theory

For the purpose of describing the scattering strength, independently of the propagation effects that are included in reverberation modelling, a review of scattering theory is useful. The graphic in Figure 1 shows the scattering geometry and defines the incident and scattered grazing angles as θ_i and θ_s respectively. The out of plane angle is φ. For monostatic backscattering, when source and receiver are collocated, $\varphi=180°$ and $\theta_i=\theta_s$. Normal incidence is $\theta_i=90°$. Specular forward scatter is $\varphi=0°$ and $\theta_i=\theta_s$. The bistatic angle is sometimes defined as the angle between the source and receiver planes, which in the figure would be 180°-φ. In other literature, the term bistatic is applied to any scattering in which $\theta_i \neq \theta_s$, and this more general definition will be used through out this paper. In all the succeeding equations, the acoustic wavenumber is $k=2\pi f/c$, depending on the frequency and sound speed of the water.

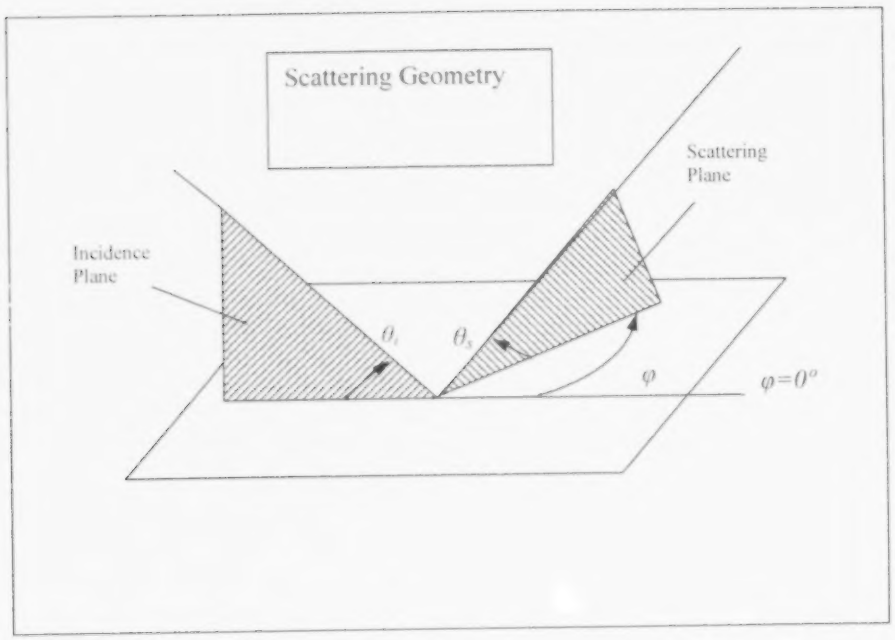

Figure 1. *Scattering geometry with grazing angles defined for the general case.*

4.1.1 Composite Roughness

The most rigorous scattering theory is the theory of composite roughness. This theory hypothesizes that scattering is really composed of two types of interactions: reflections from planes and facets of large-scale roughness and resonant interactions from small-scale roughness.

4.1.1.1 Facet Scatter or the Kirchhoff Forward Lobe

At angles near normal and for forward scatter, the large-scale roughness features provide planes or facets that specularly scatter both coherent and incoherent sound. The equations that predict this type of facet scatter all rely on the probability that the facet will be tilted sufficiently to provide a specular path from source to receiver, thus one required input is either the RMS slope of the scattering surface or the RMS height and correlation length. These types of models are well suited to bistatic and out-of-plane predictions because they are expressible geometrically. For surfaces with Gaussian statistics, the scattering strength has the form

$$S_{facet} = 10 \log\left(A \exp\left[-.5\left(\theta_o / \theta_{rms}\right)^2\right]\right)$$

where, θ_0 represents the local surface slope, θ_{rms} is the RMS slope and is related to the RMS height H_{rms} and the correlation length L by the relation $\theta_{rms} = \sqrt{2}\, H_{rms}/L$, and A depends on the surface statistics. The application of this theory to forward scatter has proven successful on most of the surfaces to which it has been applied and is used in one form or another to model high angle backscatter on both the ocean surface and the ocean bottom. In the case of backscattering from surfaces of moderate slopes, such as those likely to be encountered on the ocean bottom, S_{facet} contributes only in a cone about the specular path that is about 20° wide and, therefore, it is not generally important for the shallow grazing angles and bistatic angles less than 130° that comprise the low frequency active applications.

4.1.1.2 Bragg Scatter

For low grazing angles, composite roughness theory predicts that scattering is caused by a resonant interaction between the incident sound and the particular components of the roughness that have spatial wavelengths equal to twice that of the incident sound. This resonance is similar to a diffraction grating phenomenon and is often referred to as Bragg scattering. The equations that predict this type of resonance scatter all depend upon the magnitude of the surface height power spectrum $W(K)$ at the resonance wavenumber $K = k(\cos\theta_i + \cos\theta_s)$.

$$S_{Bragg} = 10\log\left(k^4 \sin^2\theta_i \left(\sin\theta_i + \sin\theta_s\right)^2 W(K)/4\pi K\right)$$

The frequency dependence of this theory is controlled by the assumed wavenumber dependence of the spectrum W as well as the fourth power of the wavenumber k. For example, for surfaces with spectra proportional to K^{-3}, such as major portions of the ocean wave height spectrum, this equation would be independent of frequency.

The resonance model is based solely on the physical structure of the (infinitely thin) reflecting plane and does not include volume scattering effects that become important at very shallow grazing angles. Effects such as sediment penetration and refraction are not modeled. Consequently, the fourth power dependence on the grazing angle causes S_{Bragg} to be in serious error below 20° for ocean sediments, with predictions too low on most types of surfaces to which it is applied. Shadowing and large-scale surface tilting corrections help mitigate this error but the results are still found to be low. On the other hand, the resonance model does a very good job of explaining ocean surface wave scattering when bubble clouds are not present.

4.1.2 Lambert's Rule

Lambert's Rule (also referred to as Lambert's Law) is a very simplified way of describing sound scattering from the sea floor. It assumes the sound is scattered equally in all directions, that is, diffusely rather than specularly. The scattering strength is defined as a function of the incident grazing angle, the reflected grazing angle, and a magnitude called the Lambert coefficient μ. Mackenzie who was the first acoustician to study this rule, fitted the coefficient to experimental data and obtained $\mu = .002$ or –27dB, hence, this value has become known as the Mackenzie coefficient. The equation for scattering strength under Lambert's Rule is given by

$$S_{Lambert} = 10\log(\mu \sin\theta_i \sin\theta_s)$$

This formulation is not a rigorous theoretical result; it is viewed by most acousticians as a simple geometrical argument but it has the virtue of fitting the angle dependence of a lot of

observed bottom scattering data at moderate grazing angles (20-60° range). In particular, the bistatic dependence of Lambert's law was examined by Schmidt[19], who found good agreement with bottom scattering data for incident angles from 3.5° to 78° and scattered return angles from 21° to 84°.

Because of the relative simplicity of this equation, many researchers have criticized its use, citing its lack of frequency dependence and lack of relationship to sediment properties of roughness, density, penetratibility, etc. However, Preston[20] defends the use of Lambert's rule by pointing out that the Lambert coefficient can be defined to be dependent on frequency, sediment content, and roughness. He has obtained good data comparisons when using μ ranging from –32 to –37 dB in flat sandy bottoms and ranging from –22 to –27 dB over rocky outcroppings. Preston cites four references in which good matches with data were also found using Lambert's Rule coupled with a facet term such as those listed in section 4.1.1.1. In Preston's inversions for geoacoustic parameters from measured reverberation, he used this simple equation whenever he modelled the bottom as a half-space, and he found it considerably easier to fit the single parameter μ to data than to fit 9 parameters that are required by the Mourad/Jackson Scattering Model, which follows in section 4.2.3.

4.1.3 Omni Scattering

The general form of omni-directional scattering (also called the Lommel-Seeliger law) is dependent only on the incident grazing angle θ_i

$$S_{omni} = 10 \log (\mu \sin \theta_i)$$

where, as with Lambert's Rule, the coefficient μ can be dependent upon the surface material properties and possibly frequency and azimuthal angle. This theory features a first power dependence on the sine of the grazing angle, so in monostatic backscattering cases, it falls off more slowly with grazing angle than Lambert's rule. McCammon[21] fitted an omni-directional coefficient to older published data and obtained the values listed in Table 2.

Table 2. Empirical relationships between omni coefficients and sediment properties or descriptions from McCammon[21].

OMNI COEF (DB)	SEDIMENT DESCRIPTION	SEDIMENT DENSITY	MGS PROVINCE
18.7	Rock, coarse sand, shell	Greater than 2.2	7-9
27.5	Fine sand, silt	1.7-2.2	1-4
33.5	Clay, mud	Less than 1.7	5-6

4.1.4 Summary of Scattering Theories

There are some clear differences between these three low angle scattering theories: composite-roughness Bragg resonance, Lambert's Rule and the omni-directional model. For low grazing angle dependence, monostatic backscattering models based on omni scatter have a first power dependence on $\sin \theta_i$. Lambert's law is proportional to the square of $\sin \theta_i$ and the Bragg theory varies as the fourth power of $\sin \theta_i$. Figure 2 displays a plot of the angular

dependence of Lambert's Rule and the omni-directional scattering theory for the grazing angles below 30°. Caruthers[22] argues that at these low angles the scattering is really coming from a distribution of angles and he has shown that a convolution of Lambert's law with a Gaussian probability of angular distribution would cause the scattering strength to flatten out toward grazing. His results, shown in the inset, for RMS angle spreads 0°-10°, indicate that for a wide beam system or for a rough sediment, Lambert's law should be perturbed into a dependence more like the omni-directional theory. This may explain why McCammon[21] found the omni-directional theory provided a better fit to many low angle data while others found the Lambert angle dependence better. It seems clear that scattering falls somewhere in between these two, depending on the type of sediment.

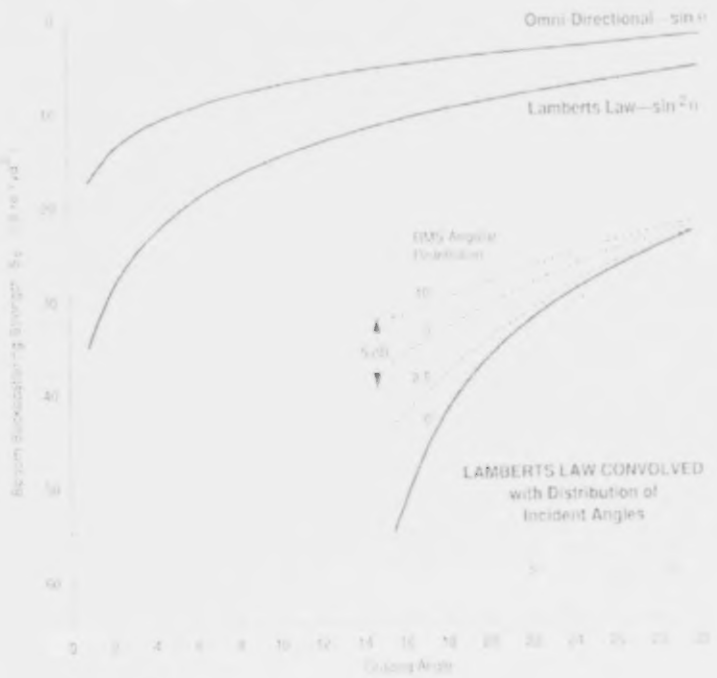

Figure 2. *Two scattering angle dependencies, sin θ and sin²θ. Inset figure shows convolution of Lambert with a distribution of angles and suggests how these two theories could be rationalized.*

With respect to frequency, the omni model and Lambert's law have an unknown empirical dependence whereas, in the Bragg theory, the dependence varies according to the shape of the surface height spectrum.

4.2 Bottom Scattering Strength

4.2.1 Ellis and Crowe 3-D scattering function

To improve on Lambert's Rule at high grazing angles where the difference between scattering and reflection from the fathometer returns starts to blur, in 1991 Ellis and Crowe[23] developed a facet term to express the high angle reflectivity from facet-like planes (following the physics of the Kirchhoff term in Composite Roughness). The Ellis and Crowe facet term requires two coefficients; υ is the facet strength and σ is the facet width or RMS slope assuming a Gaussian random surface. Values for these two coefficients are suggested to be facet width $\sigma = 10°$ and facet strength $\upsilon = \Re$, the sea floor reflection loss at normal incidence, in other words, the bottom loss. The general expression for this facet term is

$$S_{E\&C} = \upsilon(1 + \Delta\Omega)^2 \exp\{-\Delta\Omega / 2\sigma^2\}$$

where the symbol $\Delta\Omega$ is a measure of the deflection of the scattered ray from the specularly reflected ray.

$$\Delta\Omega = (\cos^2\theta_i + \cos^2\theta_s - 2\cos\theta_i \cos\theta_s \cos\varphi) / (\sin\theta_i + \sin\theta_s)^2$$

For specular scattering, $\Delta\Omega = 0$. For backscattering, $\Delta\Omega = \cot^2\theta$. This facet term is combined with the Lambert's Rule equation to create a complete scattering function. The value of this expression is its geometric generality, making it useful for bistatic applications.

4.2.2 Caruthers and Novarini Forward Scatter Lobe

In 1993, Caruthers and Novarini[24] published a slightly more generalized facet equation in which the facet is permitted to have slopes in two directions, i.e. σ_x and σ_y, and the coefficient is augmented by the exponential factor $exp(-g^2/2)$, g being the Rayleigh Roughness Parameter of the surface. ($g = 2kh\sin\theta$). They teamed their facet term with the Lambert's Rule term and named the resulting model BISSM. The suggested frequency range of their model is 500 Hz to 3 kHz.[25] This formulation could be useful where the directional slopes were known and sufficiently different, such as down a trough, but in general it would be hard to provide these values.

4.2.3 Mourad/Jackson Scattering Model

A highly complex physics-based model of low frequency bottom backscatter by Mourad and Jackson[26] was first published in 1993 and was formulated to account for shallow water data. The creators had previously published [27,28] a high frequency scattering strength model in 1989 and have extended and tested this model in 1998 [29] for the 10 - 100 kHz range.

The low frequency model assumes the backscattered field can be described by the sum of four components. The first term comes from the perturbation theory for uncorrelated scattering at low grazing angles and the second comes from Kirchhoff theory for high grazing angles. (These two terms are from the composite roughness theory). The third term is defined for very rough surfaces at low grazing angles, where perturbation theory is not valid. The fourth term is an averaged cross section to describe scattering from the sediment volume below the surface. In the combination of these scattering terms for a particular grazing angle and set of seafloor conditions, additional terms are defined; one to account for shadowing by locally tilted regions of the seabed; one to provide a slope averaging, and one to interpolate smoothly between all the terms. The model is too mathematically complicated to reproduce in this report, but there is a highly detailed derivation of this model and its component terms

in Preston[20]. Table 3 lists the input parameters needed for the low frequency model using the symbols from Preston's thesis. The most difficult term to obtain values for is the volume scattering strength parameter. Suggested ranges for this parameter are 0.0005 to 0.002 and it is clearly a fudge factor to cover the unknown properties of the volume of sediment. A table taken the APL/UW High frequency models handbook[30] shows many of these inputs by sediment name and is reproduced here in Figure 3.

Regions of validity for this model or its various components are somewhat vague[29] and the creators have used variants of this model over an extremely wide frequency range from 100 Hz to 100 kHz. Preston reports that Mourad and Jackson observed that the model usually predicts a drop in scattering strength going from 100 Hz to 1000 Hz. It predicts that volume scattering rather than interface scattering is the dominant mechanism below 1000 Hz at all grazing angles less than 70°. Where as, for higher frequencies over fast sediments, the model predicts that interface scattering dominates.

Table 3. Input parameter list for Mourad/Jackson bottom scattering model from Preston[20]

PARAMETER SYMBOL	PARAMETER DISCRIPTION
f	Frequency
c_0	Water sound speed at the sea bottom
ρ	Density ratio of sediment to water
v	Ratio of sediment sound speed at sea bottom interface to water sound speed at sea bottom
g	Sediment sound speed gradient at sea bottom
δ	Sediment loss tangent (function of sediment attenuation)
γ	Interface roughness spectral exponent
w_2	Interface roughness spectral strength
σ_2	Volume scattering strength parameter

Table 2. Model inputs in terms of sediment name.

Sediment Name	Bulk Grain Size M_ϕ	Density Ratio ρ	Sound Speed Ratio	Loss Parameter δ	Volume Parameter η_v	Spectral Exponent γ	Spectral Strength α_v (m^{-3})
Rough Rock	—	2.50	2.50	0.01374	0.002	3.25	0.2e+00
Rock	—	2.50	2.50	0.01374	0.002	3.25	0.2e+00
Cobble, Gravel, Pebble	—	2.50	1.50	0.01374	0.002	3.25	0.01e+00
Sandy Gravel	-2.0	2.402	1.4570	0.01295	0.002	3.25	0.01e+00
Very Coarse Sand	-0.5	2.301	1.3067	0.01160	0.002	3.25	0.01e+00
Muddy Sandy Gravel	0	2.274	1.2775	0.01135	0.002	3.25	0.01e+00
Coarse Sand, Gravelly Sand	0.5	2.250	1.2503	0.01116	0.002	3.25	0.01e+00
Gravelly Muddy Sand	1.0	2.153	1.2241	0.01045	0.002	3.25	0.01e+00
Medium Sand	1.5	1.945	1.1762	0.00852	0.002	3.25	0.01e+00
Muddy Gravel	2.0	1.815	1.1500	0.00810	0.002	3.25	0.01e+00
Fine Sand, V.Fs, Sm2	2.5	1.451	1.1075	0.00602	0.002	3.25	0.01e+00
Muddy Sand	3.0	1.339	1.0800	0.00528	0.002	3.25	0.01e+00
Very Fine Sand	3.5	1.266	1.0565	0.00475	0.002	3.25	0.01e+00
Coarse Silt	4.0	1.224	1.0362	0.00439	0.002	3.25	0.01e+00
Coarse Silt	4.5	1.195	1.0179	0.00416	0.002	3.25	0.01e+00
Sandy Silt, Gravelly Mud	5.0	1.169	1.0000	0.00393	0.002	3.25	0.01e+00
Medium Silt, Sandy Silt, Clay	5.5	1.149	0.9835	0.00376	0.001	3.25	0.01e+00
Sandy Mud	6.0	1.139	0.9675	0.00366	0.001	3.25	0.01e+00
Fine Silt, Coarse Clay	6.5	1.128	0.9521	0.00356	0.001	3.25	0.01e+00
Sandy Clay	7.0	1.118	0.9429	0.00342	0.001	3.25	0.01e+00
Very Fine Silt	7.5	1.147	0.9337	0.00343	0.001	3.25	0.01e+00
Silty Clay	8.0	1.20	0.9624	0.00367	0.001	3.25	0.01e+00
Clay, Fine Clay	9.0	1.145	0.9000	0.00328	0.001	3.25	0.01e+00

Figure 3. Sediment input parameter table from APL/UW high-frequency models handbook[30]

4.2.4 Holland and Neumann

In 1998, Holland and Neumann[31] proposed a model for the 100 Hz – 1000 Hz scattering from inhonogeneities within the sediment and sub-bottom horizons. They define scattering from a lens embedded within a host sediment, whose properties are tied to the geoacoustic properties used to compute the bottom loss, thereby making the scattering model self-consistent with a loss model. The inputs to this scattering model are the sound speed ratio, gradient, density and attenuation of the scatterers and the host sediments, as well as an estimate of the aspect ratio of the scatterers. They have demonstrated success against measured data, particularly at low grazing angles.

4.2.5 Opinions on Bottom Scattering Strength Models

Not Recommended

The use of Lambert's rule or the Omni Rule would be a very crude estimate of the complex nature of bottom scattering strength. The Ellis & Crowe model has a slightly simpler facet term than the Caruthers & Novarini, but both of them rely on Lambert's rule for the low angle scatter and therefore are 'low-tech'.

Recommended

The Mourad/Jackson model has had a lot of research poured into it. It represents the best attempt to model the diverse scattering mechanisms over a very wide frequency range and sediment type. Although it is criticized for having too many parameters that are poorly known in most areas, particularly the volume parameter that covers a host of mechanisms within the sediment, still, it represents the best available attempt to scientifically quantify scattering strength. In the same vein, the Holland and Neumann sediment volume scattering strength is the newest and most physical explanation for this deeper scatter mechanism and it may be advantageous to replace the volume term in Mourad /Jackson with this one. In both models' cases the inputs will be hard to supply, however at worst, a crude estimate of some of the parameters is probably just as good as guessing a value for the Mackenzie coefficient of Lambert's rule.

4.3 Surface Scattering Strength

4.3.1 McDaniel

In 1993, Suzanne McDaniel[32] published a good review of theories and data relating to sea surface reverberation between 3 kHz and 60 kHz. She champions the use of Composite Roughness theory for modelling the surface scattering, combined with a bubble scattering term. She states that high grazing angle scattering is due to the rough ocean surface while low grazing angle scattering comes from resonant sub-surface microbubbles. The major input for this model is the sea surface spectrum of waveheights. McDaniel and McCammon[33] applied the composite roughness model to fetch limited seas and published a fetch dependent sea surface wavenumber spectrum in 1987.

4.3.2 Ogden-Erskine

In 1992, Ogden and Erskine[34] produced a set of empirically derived equations to predict low frequency surface scattering strength. An attempt to extend these expressions to the bistatic case was made by Vendetti[35] in 1993. Improvements to this theory are given in Nicholas, Ogden and Erskine[36] in 1998. The basic theory contains two parts, depending on the wind speed.

Low wind speed, $U \le minimum(41.71 - 0.1155 f, 14.0)$, f in Hz, U in knots.

$$S_{O\&E} = 10\log_{10}\left\{1.61\times10^{-4}\tan^2\theta_i\tan^2\theta_s\exp\left\{-1.43\times10^{7}/(f^2U^4\cos\theta_i\cos\theta_s)\right\}\right\} \quad \cdots \theta_i,\theta_s < 45$$

$$= 10\log_{10}\left\{1.61\times10^{-4}\sqrt{2}\sin\theta_i\exp\left\{-1.43\times10^{7}/(f^2U^4\cos^2 45^\circ)\right\}\right\} \quad \cdots \theta_i,\theta_s \ge 45$$

The high wind speed portion comes from the empirical curves from Chapman-Harris.
High wind speed, $U \ge 39.07 - 0.066\,f + 7.06\times10^{-5} f^2 - 2.58\times10^{-8} f^3$

$$S_{O\&E} = 3.3\beta \log_{10}(\sqrt{\theta_i \theta_s}\ /30) - 42.4 \log_{10} \beta + 2.6$$

$$\beta = 158\,(Uf^{1/3})^{-0.58}$$

If the wind speed is below the Chapman-Harris limit but above the low wind speed limit, a linear interpolation in DB space is used to obtain the scattering strength. The expressions are said to be valid from 50 and 1000 Hz, but have been used at higher frequencies.

4.3.3 Gilbert Bubble Model

The Gilbert model[37] published in 1993 is a treatment of the contribution from the clouds of subsurface bubbles that enhance low-angle scattering. To complete the application of this theory, an empirically derived relation between the sound speed fluctuation and the wind speed, c_f=*0.00135* $U^{3.3}$ is obtained by visually matching the Ogden-Erskine model. The values obtained from this theory are similar to those of the Ogden-Erskine model in the region of Chapman-Harris (high winds) but the advantage of the Gilbert theory is that the bistatic angular dependence may be more geometrically accurate.

$$S_{G} = 10 \log_{10} \left\{ \frac{3Lk^4}{4\pi^2 c^2} \left[\frac{4k_z^4 L^4}{(1+4k_z^2 L^2)(1+k_z^2 L^2)} \right] 1.6 c_f^2 (k\cos\theta_i + k\cos\theta_s)^{-3.86} \right\}$$

where L is the e-folding distance, usually set to 1.9; c is the sound speed; k is the acoustic average wavenumber, $2\pi f/c$; k_z is the vertical wavenumber given by $k\ sin\theta_i$; and c_f is the sound speed fluctuation. This model can be coupled with a composite roughness model for lower wind speed scattering.

4.3.4 3D Gauss Combination Model

In 2000, Gauss, Fialkowski, Wurmser and Nero[38] described a broadband 3D model for surface scatter in the 50-5000 Hz frequency range based on a small slopes approximation and a power law spectral representation of the ocean surface. The bubble cloud scattering model is derived from Gilbert and an empirical relationship between the e-folding distance and the wind speed is based on measurements in the CST-& trials. This model is physics-based and multistatic, however it contains four parameters that were matched to data, making it actually a combination of empirical and physical.

4.3.5 Opinions on Surface Scattering Strength Models

Not Recommended

The Ogden / Erskine model is entirely empirical and represents an extension to the Chapman Harris equations that have been around for a long time. It is not readily applicable to bistatic applications.

Recommended

The Gilbert Bubble model presents a good physical explanation for high wind speed scattering. Coupling this with the composite roughness terms outlined by McDaniel or utilizing the combination model in Gauss would give the best surface scattering strength model. In the Gauss model, it is not clear how they are representing the sound speed fluctuation so more research is warranted for this model.

4.4 Volume Scattering Strength

In 2000, Gauss, Fialkowski, Wurmser and Nero[18] described a volume scattering theory based on acoustic interactions with fish swimbladders. The model is developed for the frequency range 50 to 5000 Hz for small-sized fish schools and includes all orders of multiple scattering interactions between the fish. It also incorporates boundary-interference effects for both the ocean surface and the bottom. The inputs are fish-distribution algorithms.

In 2003, Love, Thompson and Nero[19] documented the changes in volume reverberation under 10 kHz from deep to shallow water. This paper provides additional information about the swimbladder model and lists fish radii distributions for inputs.

4.4.1 Opinions on Volume Scattering Strength Model

There are very few physics-based models of fish interactions. This model may be worth investigating in more detail, although the first reference article is sketchy.

4.5 APL/UW High-Frequency Acoustic Models Handbook

In October 1994, the Applied Physics Laboratory of the University of Washington (APL/UW) issued a compendium of models called the High-Frequency Acoustic Models Handbook[20] designed or selected specifically for use in the frequency range 10 kHz to 60 kHz. The contact personnel are listed as Chris Eggen (206-543-9804), chris@apl.washington.edu and Kevin Williams (206-543-3949), williams@apl.washington.edu. This document contains equations representing the current best descriptions for each of the topics. The Oceanic and Atmospheric Master Library (OAML) has designated five of these models to be official U.S. Navy Standard models for high frequency sonar and weapon modeling usage. They approved the Francois-Garrison absorption model, the surface and bottom loss models and the surface and bottom back scattering strength models, and these are listed in OAML under the collective umbrella acronym HFEVA.. A summary of the contents of the handbook is shown in Table 4.

Table 4. APL/UW high frequency models handbook contents summary[30]

CHAPTER HEADING	TOPICS
Volume	Sound speed models: Chen-Millero-Li, Mackenzie
	Absorption coefficient: Francois-Garrison
	Backscattering column strengths defined geographically
	Scattering layer empirical model
	Volume induced spectral spreading empirical model
Surface	Wind and sea state relationships
	Bubble backscattering: McDaniel and Gorman
	Sea surface roughness scattering using Composite Roughness theory: McDaniel
	Spectral spread empirical model
	Forward loss and absorption from near-surface bubbles
	Coherent reflection loss
	Surface reflection statistics
	Ambient noise, surface radiation patterns, wind and rain effects
Biological Noise	Frequency distribution of biological sources
	Marine mammal ambient noise spectra
	Snapping shrimp and other invertebrate noise sources
Bottom	Sediment descriptions by grain size and name
	Forward loss: lossy Rayleigh reflection coefficient
	Backscattering strength: Mourad/Jackson
	Bistatic scattering: generalization of Mourad/Jackson
Arctic	Sound speed and attenuation of ice
	Scattering and forward energy loss from un-ridged ice, empirical
	Ice keel reflections, directional patterns and statistics

It is instructive to consider the estimates of uncertainty in the models of HFEVA. The models handbook contains a discussion of the dB variability that should be tacked onto every model prediction (something that every modeller should supply, but almost no one else does). Table 5 lists the dB variability associated with surface and bottom losses and backscattering strengths that were published in the report. Note the sheer size of the errors over soft bottoms.

Table 5. Uncertainty in HFEVA predictions from[30].

MODEL	ENVIRONMENT	DB VARIABILITY
Surface Backscatter	Wind speed greater than 16 knots	±4
	Wind speed less than 16 knots	±5
Surface Loss		-3 to +5
Bottom Backscatter	Rock and Gravel	±10 above 15 ° greater than ±10 for shallower angles
	Well characterized sand and silt	±3
	Poorly characterized sand and silt	±5 and ±10
	Soft bottoms	±15 to ±30
Bottom Loss	Error is the same magnitude as the loss	i.e. 4dB loss ±4

4.5.1 Opinions on the APL/UW High Frequency Models in HFEVA

The models in HFEVA are written for the frequency range starting at 10 kHz. Most of them are entirely empirical, and they are designed for the weapon models. I would hope and expect that the lower frequency models covered in sections 4.2 and 4.3 would be able to operate up to the 15 kHz limit so that we could have a continuous coverage. I would not recommend implementing the HFEVA models because of the potentially large disjoint between them and the lower frequency models.

4.6 Fluctuation Statistics

The fluctuations in acoustic pressure amplitudes (variations about some mean level) can be caused by many things, such as randomness within the propagation channel, surface motion, internal waves, microstructure, etc. These fluctuations are considered to be random processes that are described by statistical distributions. One common method of displaying and analyzing the fluctuations of a signal is the histogram or probability density function (*pdf*), in which the y axis shows the number of times the signal has an amplitude within a specified range (bin size) and the x axis covers the entire range of amplitude values.

The area under the probability density function to some amplitude A is given by the cumulative distribution function (*cdf*). This is the probability that a fluctuation will be of amplitude A or less. The probability that the amplitude will be A or higher is given by *1-cdf*, defined as the probability of false alarm (*pfa*). Thus, the *pfa* describes the high amplitude, low probability portion of the fluctuation and is the most important statistical descriptor for the target detection process. The utility of the *pfa* curve is that it highlights the area under the tail of the density function, where the occasional high bursts of reverberation are found.

The Rayleigh distribution is the statistical family of the amplitudes of a zero mean Gaussian random signal. Generally, ambient noise is found to be Rayleigh although in 1996

George[40] reported non-Gaussian distributions from shipping noise in shallow water. High frequency surface reverberation is by in large found to be Rayleigh, however shallow water sediment reverberation has shown significant deviations from Rayleigh at frequencies spanning 400 Hz to 35 kHz.

In 1997, Linda Deliman (now Linda Sheckler) wrote her PhD thesis[41] on the topic of mechanisms that cause changes to bottom reverberation statistics. Her thesis contains a detailed review of scattering theories and also has a good discussion of most of the common statistical distributions and statistical tests of goodness-of-fit. She processed shallow water data collected during two SACLANT Centre experiments, including low-frequency measurements made over chalk and clay sediments with varying degrees of roughness using different pulse types and pulse lengths. Her data revealed the fluctuation statistics both Rayleigh and non-Rayleigh. She then conducted simulations to determine the causes of these changes in distribution. Her conclusion was that sediment type, pulse type, and pulse length were not a factor *per se* in the deviations of the statistics from Rayleigh. However, sediment "patchiness", defined as an ensonified area containing patches that contribute largely different backscattering strengths within the area, does cause the statistics to deviate from Rayleigh.

In 1999, Dorfman and Dyer[42] analyzed ONR ARSRP-93 experimental data taken over very rough bottoms at 230 Hz. They found the reverberation envelope was strongly non-Rayleigh, with the degree of departure from Rayleigh being dependent upon the bistatic and vertical grazing angles.

4.6.1 Rayleigh Statistics

The Rayleigh probability density function for an amplitude x (generated from zero mean Gaussian random components with variance δ^2) is given by

$$pdf_{Rayleigh}(x) = x/\delta^2 \exp^{-x^2/2\delta^2}$$

The mean and variance for this pdf are

$$\mu_{Rayleigh} = \delta\sqrt{\pi/2}$$

$$\sigma^2_{Rayleigh} = \delta^2(2 - \pi/2)$$

Often, the data can be normalized to obtain a mean value of unity. In that case, the value of δ in the above equations is fixed, $\mu_{Rayleigh} = 1$, $\delta = \sqrt{2/\pi}$, $\sigma^2_{Rayleigh} = .2732$. Therefore, if the normalized reverberation amplitude fluctuations follow a Rayleigh distribution with unity mean, the spread of the density function is defined by the standard deviation $\sigma_{Rayleigh} = 0.5227$.

The probability of false alarm for Rayleigh distributions is

$$pfa_{Rayleigh}(A) = e^{-A^2\pi/4}.$$

Figure 4 displays two Rayleigh *pdf*s, the noise curve and the signal&noise curve. The probability of detection *pd*, and probability of false alarm, *pfa*, are determined by the areas under the overlapping probability curves. The region of overlap is defined by the strength of the noise, the signal, the defined threshold and the statistical *pdf* distribution.

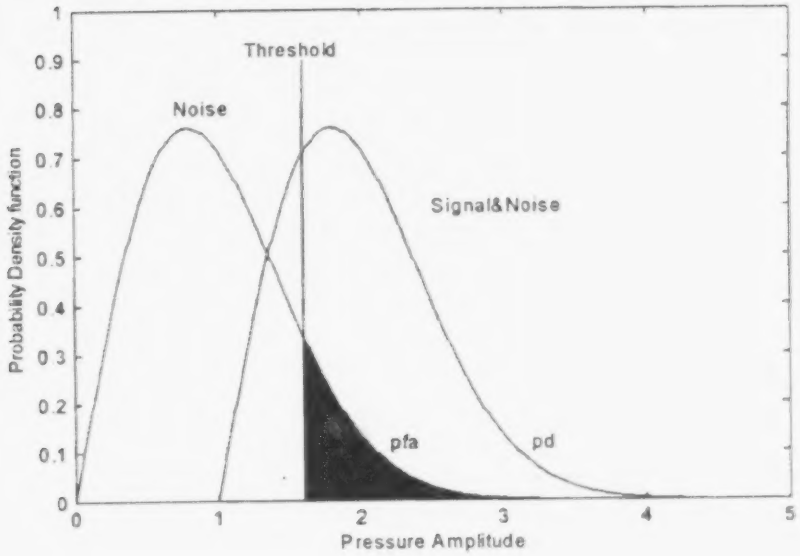

Figure 4. *Rayleigh pdfs for noise and signal&noise. Threshold location defines the areas labelled pfa (black) and pd.*

4.6.2 Rician Distribution

The Rician (also called the Generalized Rayleigh or Rayleigh-Rice) distribution is used to represent echo fluctuations that contain both the steady-state component of the coherent reflected (specular) field and the random component of the diffuse scattered sound field. For very smooth surfaces, the coherent energy dominates the received signal and the statistics are Gaussian, while for very rough surfaces the diffuse field dominates and the received signal becomes completely random yielding Rayleigh statistics. The Rician probability density function containing both coherent (y) and diffuse (x) components is

$$pdf_{Rician}(x,y) = x/\delta^2 \, e^{-(x^2+y^2)/2\delta^2} \quad I_0\left(\frac{xy}{\delta^2}\right)$$

where I_0 is the modified Bessel Function, and y is related to the signal-to-noise ratio.

In 1985, Tim Stanton[43] used the Rician distribution to characterize the echo fluctuations due to small-scale roughness from a rough sea floor. He extracted RMS

roughness and correlation functions from published data, then applied it to other sonars with good success.

4.6.3 Mixture Distribution

In 1998, McCammon, Gilbert and Sheckler[44] derived a mixture model to fit bottom reverberation data measured in the Celtic Duet experiment. An example of the data's high reverberation spikes is shown in Figure 5, which displays the probability of false alarm and fluctuation histogram for an HFM signal. Following the discoveries of Sheckler's thesis concerning the necessity for sediment patchiness to create non-Rayleighness, a two-component model was selected. This has the virtue of being a physically meaningful model because its two free parameters can be related to the measurable quantities of scattering strength contrast between two different types of sediments and fraction of area that these different types occupy. The two free parameters are ε, the fraction of the lesser common sediment type, and γ, the ratio of scattering strength mean levels of the two sediments. The model is

$$pdf_{mixture}(x) = \pi\alpha^2 x/2\left[(1-\varepsilon)e^{-\pi\alpha^2 x^2/4} + (\varepsilon/\gamma^2)e^{-\pi\alpha\, x^2/4\gamma^2}\right]$$

$$pfa_{mixture}(A) = (1-\varepsilon)e^{-\pi\alpha^2 A^2/4} \quad + \quad \varepsilon e^{-\pi\alpha\, A^2/4\gamma^2}$$

$$\alpha = 1+\varepsilon(\gamma-1)$$

Two regression formulas were derived from the experimental data to relate the mixture parameters $[\varepsilon,\gamma]$ to the standard deviation of the scattering strength or the reverberation amplitude time series. These relationships are

$$\gamma = 6.2373(\sigma - 0.5227)+1 \qquad \textit{for amplitude data}$$

$$= 0.912(\sigma_{dB} - 5.566)+1 \qquad \textit{for level data}$$

$$\varepsilon = \exp\{-1.4352(\gamma-1)\}$$

Note that the model is very sensitive to the choice of γ, and by empirical extension, it will be very sensitive to the value of σ or σ_{dB}. For default values, when there is no knowledge available, the recommended values are averages taken from the data, $[\varepsilon,\gamma]$=[0.44,1.57].

Dorfman and Dyer[42] also suggested a mixture model for their rough bottom observations. They suggest adopting a continuous scattering model having a Rayleigh envelope added to a discrete scattering model (arising from a small number of individual features within the sonar footprint) having a K-distribution. These models, plus a heuristic mechanism of self-selection within the discrete scattering model, could explain the observed angle dependence of the reverberation statistics they measured.

4.6.4 Opinions on Statistical Models for Reverberation

I think it is very important to use the proper statistics to generate the reverberation and noise portions of a received signal. The amplitude and placement of high spikes in a time series is a critically important part of the signal character if the signal is to be used for testing detection algorithms. Since the sea bottom is so inherently variable, either of the mixture

models could be made applicable, so I recommend their use, possibly in combination with the coherent component from the Rician distribution in the case of forward scattering.

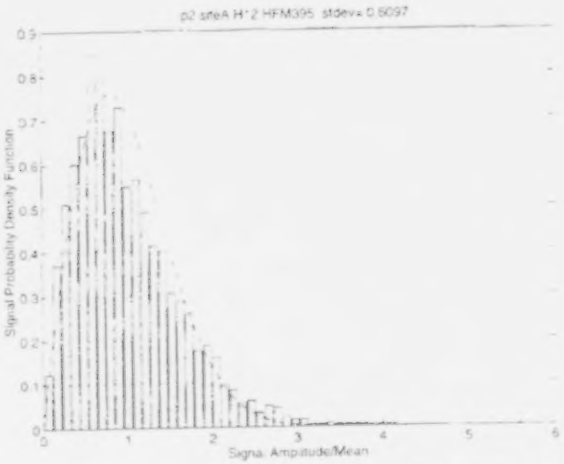

Figure 5-25. Signal fluctuation histogram. Site A 395 Hz HFM.

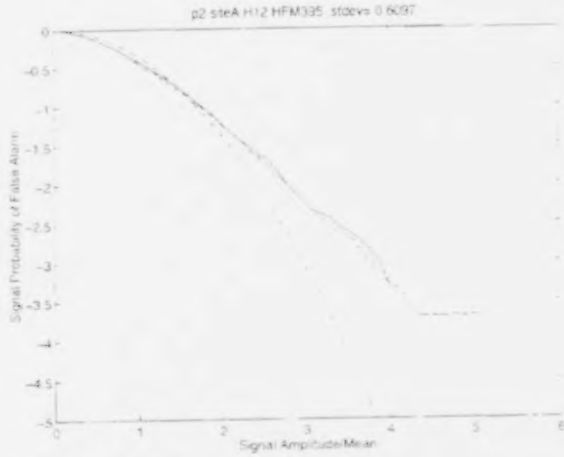

Figure 5-26. Signal log PFA. Site A 395 Hz HFM, for two sampling intervals: 0.4 seconds/sample (solid line) and 0.1 seconds/sample (dashed-dot line).

Figure 5. *Data showing non-Rayleigh statistics from Deliman*[41]

4.6.5 Propagation Statistics

In 2001, Wolfson and Tomsovic[45] studied long-range propagation fluctuations and found that the stability of the rays was consistent with log-normal densities. They cite experiments by Colosi et al.[46] that also found long-normal densities of wave-field intensities.

4.7 Coherence Lengths and Times

In 2004, Peter Dahl[47] published a model for generating the spatial coherence of sound that has been forward scattered from the sea surface. He applied the van Cittert-Zernike theorem using the sea surface as the intensity source and his appendix gives an improved method for estimating the 2D autocorrelation function for sea surface waveheight variations. His paper derives simple expressions for the characteristic length scales of vertical and horizontal coherence. Data comparisons are shown. In 2001, Dahl[48] also published measurements made at 10 kHz of time and angle spreading from the sea surface and used Fourier transforms to derive the related spatial coherence separations.

In 1998, William Carey[49] published some measured horizontal coherence lengths at 400 Hz in both shallow and deep water. He obtained 100 wavelengths in deep water out to ranges of 500 km, while in shallow water he obtained 30 wavelengths to ranges of 45 km. The 100 wavelength value was corroborated by Oba and Finette[50] in 2002 in a numerical experiment with internal waves. Carey outlines models that use Gaussian coherence functions and applies his results to the computation of array gain. Since he states that the measurement of pair wise coherence is strongly affected by noise and multipath interference effects, these measurements could possibly be used to validate the modeling of the received signal at multiple hydrophone locations along an array.

In 2000, Finette et al[51], Headrick et al.[52] and later in 2002, Rouseff et al.[53] published papers about the 1995 shallow water experiment SWARM. This study measured the decorrelation of modal amplitudes from internal waves at 100 Hz and 400 Hz. The time scales measured were of the order of 100 seconds. The Rouseff paper gives a good mathematical description of internal waves for its examples.

In 2000, Melvin Hinich[54] described a statistical theory of signal coherence and derived a signal coherence function that measures the amount of random variation in each spectral bin.

4.8 Spreading Functions

4.8.1 Spectral Spread from the Moving Sea Surface

In 1983, McDaniel and Gorman[55] published the first development of the theory describing the physical mechanisms of frequency spreading of reverberant signals. They derived equations relating the spectral spread of the scattered signals to the ocean wave-height frequency spectrum, and published curves of normalized spectral width versus grazing angle and RMS wave height for a 20 kHz signal. In 1990, McDaniel and McCammon[56] used this formalism to study the spectral spread from surface bubble motion and they linked the spectral spread to surface descriptors of wind speed and surface friction velocity. In the 1 kHz region, they calculated spectral width increases of up to 1.5 Hz and Doppler shifts of up

to 0.5 Hz for a 30 kt wind speed, making this spectral spread a very narrowband process. Their paper includes equations for the sea surface breaking wave speed and random bubble motion correlation function.

In 2003, Robert Gragg[57] published a derivation of sea surface reverberation cross spectral densities and Doppler sidebands. The Doppler shift they showed as an example was of the order of 0.3 Hz for a 100 Hz signal in a 5 knot wind.

4.8.2 Rough Sediment Time and Angle Spread

In 1993, McCammon and Thompson[58] derived expressions for the time and angle distribution of the sound intensity incident on thin, rough sediment. The theory relies on the assumption that the scattering is caused by facet reflections and it requires as inputs the RMS slopes of both the ocean floor and the basement. Solutions for an impulse response were fitted using least-squares to obtain simplified equations for predicting spreading. The time and angle standard deviations are given as a function of the effective RMS basement slope ζ (the tangent of the RMS slope angle) and grazing angle θ (in degrees).

$$\sigma_t = \zeta^2[1.31 + 1.39\tanh(0.1\theta - 2.5)] \quad \textit{seconds}$$

$$\sigma_\theta = \zeta^2(-32.88 + 151.29\tan\theta) \quad \textit{degrees}$$

For example, the use of the first equation predicted approximately a 0.02 second pulse time elongation for typical basement slopes of 10 degrees. This effect would only be important for short pulses operating over thin sediment regions.

4.8.3 Reflection Coefficient Uncertainty

In 2003, Charles Holland[59] discussed the uncertainty associated with deriving sediment reflection coefficients and proposed that the measurement process introduces ± 0.5 to 1 dB uncertainty in level and a few tenths of a degree from 0 – 34° grazing angle, depending on the frequency and experimental geometry.

4.8.4 Sound Speed Fluctuations

In 1996, Chang and Tarng[60] looked at pulse propagation in a fluctuating ocean with a range dependent sound speed profile. They assigned the speed fluctuations to a random zero-mean function added to the deterministic profile to represent variations due to internal waves. They assume a temperature fine structure correlation function given by

$$B(r,z) = <\mu^2> e^{-|z|/z_0} e^{-r^2/l^2}$$

with typical values z_0=2 m, l=74m, and $<\mu>$ from 10^{-6} to 10^{-9}. They find the temperature fine structure causes a 2-6 msec pulse broadening, presumably because of the path length variations.

In 2003, Stanley Flatte and Michael Vera[61] published methods for computing travel time and arrival angle variances due to internal wave sound speed fluctuations. These methods involve integrations along the sound ray path of sound speed perturbations. Even though they evaluated their results using the PE at low frequencies, their equations should be valid at higher frequencies for other applications. The model for performing the integrations was called CAFI (Computation of Acoustic Fluctuations from Internal waves) written by Flatte and Rovner[62] and published in 2000.

In 2001, Siderius et. al.[63] published the data from the Advent'99 experiment conducted at SACLANTCEN in the 200-3800 Hz frequency range. They studied time variability of the acoustic measurements correlated to the time-varying sound speed profile. They also modelled the variability using the coupled mode model C-SNAP. The purpose of this experiment was to study the effect of sound speed fluctuations on the values of geoacoustic parameters obtained by inversion.

4.8.5 Bottom Layering

One feature of the 1987 Westwood and Vidmar paper[64] is the tracing of rays into the sediment and through multiple sub-surface layers. They claim there is a necessity for using complex reflection coefficients that include the conversion to shear (as a loss mechanism, not to trace shear rays) from the near-surface layers even though they are working in a 1000 Hz – 3000 Hz frequency range and it is generally thought that shear wave propagation is not an important mechanism above 200 Hz.

Of particular interest are the examples of simulated waveforms produced over these many-layered sediments. One of their figures, reproduced here in Figure 6, displays the received waveforms computed first over one layer and then over 28 layers of sediment. There is considerable temporal spreading produced by the resonance in the layering. Westwood and Vidmar make the following observations.

1. The layering depth determines the time interval over which the impulse response is smeared.
2. Layer spacing places a lower limit on the frequency band for which the effects of the layering are significant.
3. At higher frequencies, the deeper penetrating rays suffer relatively greater attenuation, which causes the smearing to decay exponentially with time.

Obtaining the precise layering information, with layers as thin as 1 meter, will be nearly impossible in any general ocean environment. Westwood and Vidmar acknowledge that the thickness of a layer and its depth have been observed to change considerably over lateral distances of about 10 km, making it difficult to predict layer properties, however they found their simulated layers could have a sizable effect on the sound level, and they cite differences of potentially up to 8 dB when traversing many sub-surface layers and ignoring shear waves in the calculation.

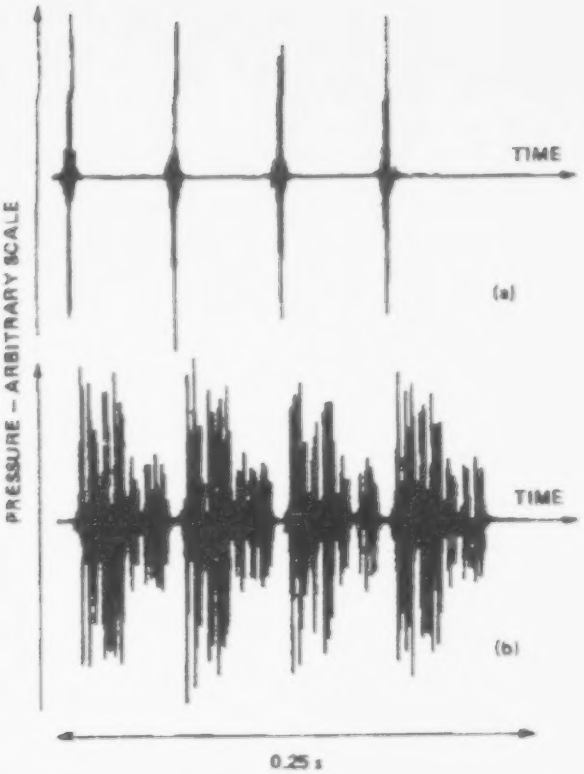

FIG. 11. Simulated waveforms using profiles having (a) one layer in the ocean bottom, (b) 28 layers in the top 40 m of the ocean bottom. Ocean depth = 5900 m, range = 10 km, source depth = 100 m, receiver depth = 50 m, total sediment thickness = 320 m.

Figure 6. Figure from Westwood and Vidmar[54]

4.8.6 Opinions on Spreading Functions

The three spreading functions from sea surface Doppler, thin sediment roughness and sound speed fluctuations outlined above are very narrow band in character, and since the inputs are not likely to be well known, it would be a guess to apply them. The spreading function from the bottom layering appears to be significant. The figure shows the simulated waveforms from 28 bottom layers were substantially filled in with temporal structure. Clearly this would be an important effect for short-range shallow water environments where one

might expect to have a lot of bottom interaction. This temporal structure came from ray tracing into the sediment and the propagation models recommended in section 2.2 would not produce this structure because they use a plane wave reflection coefficient approach to bottom loss, that is, if bottom layers are provided, the uppermost reflection coefficient is computed using a layer matrix approach, and a single ray is imbued with this amplitude. The LePage extension to PROLOS might be able to provide the required temporal differentiation and should be examined. In any case, if the propagation model doesn't produce this spreading, then an exponential time decay could be created to simulate this effect. If necessary, all these effects could be rolled into one statistical spread about the tonal. I recommend additional research on this topic.

4.9 Ambient Noise

In 1981, Walker, Crowe and Mayo[65] studied the synthesis of a time series containing noise representing distant shipping, wind generated surface noise, and self-noise. They demonstrated a technique whereby the noise was specified by its spectra and directionality through spatial correlation. Then these functions were transformed to the time domain to produce covariances. A signal was simulated from Gaussian components using these covariances. In 1996 and 1997, C.H. Harrison[66,67] derived an equation for the noise correlation function that could serve as an input to Walker's synthesis.

In 2002, Wales and Heitmeyer[68] published a model for determining an ensemble of the broadband source spectra of sound generated by merchant shipping from 30 Hz to 1200 Hz. Their paper provides a probability density for generating ship spectra that includes correlation between ship source level and ship speed. Thus, this model incorporates both the noise level and the fluctuation distribution of the shipping.

In 2001, Means and Heitmeyer[69] studied the low frequency noise produced by breaking waves. Their paper presents measurements and a model for the bubble cloud excitation and describes the spectral characteristics of the breaking wave spectra.

4.9.1 Opinions on Ambient Noise Models

The equations in Harrison together with the technique in Walker could serve to model most types of ambient noise as they are mathematically general and flexible. The Wales/Heitmeyer shipping model is useful because it contains the fluctuation statistics as well as the level. The question is whether the noise would ever become an important component in an active environment that contains reverberation. If choices have to be made for funding reasons, I would recommend investing the initial effort in the reverberation portion of the time series and planning to add the noise as a second-round improvement.

5. Source and Target Models

5.1 Source Time Series

5.1.1 Pulses

The spectrum of pulsed signals should be easy to obtain, either by reconstruction from the mathematics of the signal's equations or directly from a measurement at the source. The frequencies that will be specified for the propagation program are often just the lowest and highest frequencies in the source spectrum, if it is relatively narrowband. If these propagation loss computations differ by more than a few dB, then sub-sampling within the source spectrum may be called for.

5.1.2 SUS

SUS charges (Sound Underwater Signal) are small explosive charges that are often used as broadband sources for reverberation measurements. The SUS explosion creates an initial spike of pressure that expands outward as a shock bubble. The bubble then rhythmically collapses creating a pulse train in time. The spectrum contains energy from 10 Hz to 5000 Hz. The most up to date reference for equations that reproduce the propagation time series and spectrum of a SUS explosive is Preston[20] who based his work on that of Chapman[70]. In Preston's Appendix B, there are tables of third-octave band source spectral levels taken from SACLANTCEN measurements and there is a MATLAB coded algorithm that will compute the SUS time series and spectra.

5.2 Target Strength Models

5.2.1 Submarines

Currently in preparation at DRDC, Atlantic is a TTCP Technical Report on multistatic active acoustic target strength modelling for OR/OA applications[71]. Bearing in mind the frequency range of interest here is 500 Hz to 15,000 Hz, the following excerpts from the TTCP report deal with the frequency dependence of submarine targets:

> "In the medium-frequency regime (between 1 and 10 kHz with wavelengths between 1.5m and 15cm), the effects of material and internal structure are still present but less pronounced than they are at low frequencies. Dependence on internal structure becomes more complicated and sensitive to small changes in aspect and frequency, so changes in target strength as function of aspect and frequency may appear to be random... Fine-scale variation of target strength with frequency may be estimated as having an interference structure with frequency spacing roughly equivalent to the reciprocal of the target-induced echo spreading time... In the high-frequency regime (above 10 kHz with wavelengths smaller than 15 cm), it is mostly the exterior shape of the hull that matters. Generally, at any one aspect only three or four significant scattering centers (highlights) can be resolved by large-bandwidth, high-resolution signals and processing."

In table 2 of the TTCP report, there are nine target strength models presented. They fall for the most part into two frequency ranges: below 2000 Hz or above 20,000 Hz. The

lone exception is the DTSO facet model that is a medium fidelity model describing the submarine target as a series of facet reflectors with material properties. The frequency range for this model is stated to be from 500 Hz up. The difficulty of applying this model to the 500 to 1000 Hz target is the specification of the facet sizes and shapes, since planar facets are not able to handle the resonances that occur at these low frequencies in a finite curved body. For these latter effects, the BASIS model from DRDC, Atlantic would be suitable, and it's range of applicability is from 500 Hz to at least 2000 Hz and possibly higher.

5.2.2 Seamounts

In 1990, Preston, Akal and Berkson[72] published measurements of the scattering strength of seamounts, which are often modeled as target-like clutter. The scattering strengths from 200 to 800 Hz ranged from –22 dB to –32 dB.

5.2.3 Fish

In 2001, Cordue, Coombs and Macaulay[73] presented a linear relationship between the target strength distribution and the length of a species of fish. While the target strength was measured using a 38 kHz echo sounder, the relationship they found might be extended to lower frequencies and longer fish species.

6. Time Series Generation

In 1987, Westwood and Vidmar[64] discussed time series simulation in a layered-bottom ocean. Using ray theory, they constructed a frequency domain transfer function representing the effect of the environment on a broadband signal. This transfer function $H(f)$ is just the frequency sorted acoustic field, in which each eigenray with travel time t_i has the phase $exp(2\pi f t_i)$ added onto its complex amplitude before combining with the other eigenrays. The receiver time series is the inverse Fourier transform of the product of the source spectrum and the environmental transfer function.

$$r(t) = F^{-1}\{F\{s(t)\} \cdot H(f)\}$$

They have a nice discussion of the three mathematically equivalent methods for generating this receiver time series.

1. Combining all the eigenrays into a single transfer function and multiplying it by the source spectrum to obtain the receiver spectrum, then inverse Fourier transforming as shown in the equation above.
2. Calculating the receiver response due to each individual eigenray $H_i(f)$ and fitting them according to their travel times into the receiver time window (the time interval at the receiver for which the time series is to be generated)
3. Convolving s(t) and $h(t) = F^{-1}\{H(f)\}$ to obtain the receiver response for each eigenray and fitting them into the receiver time window.

The discussion of these three techniques concludes that the first method is feasible when the eigenray's travel times are close together, but when the difference in travel times is greater than the total time interval of the FFT, there will be wrap around to deal with. The second method requires fitting the response to each eigenray into the receiver time window, which does not, in general, coincide exactly with the time increment being used in the FFT. The third method is very inefficient compared to the other two. Westwood and Vidmar chose to implement the second method because they could then use a fairly small FFT array size to

transform the source time series without restricting the size of the receiver time window. In effect, they don't form the transfer function at all, but sort eigenrays directly into the receiver window, and combine them there.

The eigenray characteristics required for these techniques are travel time, complex reflection and transmission coefficients, refraction phase shifts, frequency dependent attenuation and spreading loss. These can be obtained from any high fidelity ray algorithm. Normal Mode theory can also be used, provided the modal group velocities are used to obtain travel time.

7. Sonar Stimulation

7.1 Stimulation Facilities

7.1.1 UWEF

The following are excerpts from an article written by J.D. Hessman[74] about the UWEF (Undersea Weapon Evaluation Facility).

In 1994, the Naval Undersea Warfare Center (NUWC) division in Keyport, Wash. and Penn State's Applied Research Laboratory (ARL) put into operation at Keyport the world's only land-based facility, the Underwater Weapon Evaluation Facility (UWEF), in which state-of-the-art torpedoes, mines and other underwater weapon systems and vehicles can be held "captive" while being reliably and realistically tested under their own power. The key component of the facility is a 4,600 cubic foot water-filled pressure vessel, 45 ft long and 12 ft in diameter shown in Figure 7. The weapon being tested operates under its own power, as it would in free-swim exercises, while experiencing computer-generated acoustic and dynamic stimuli.

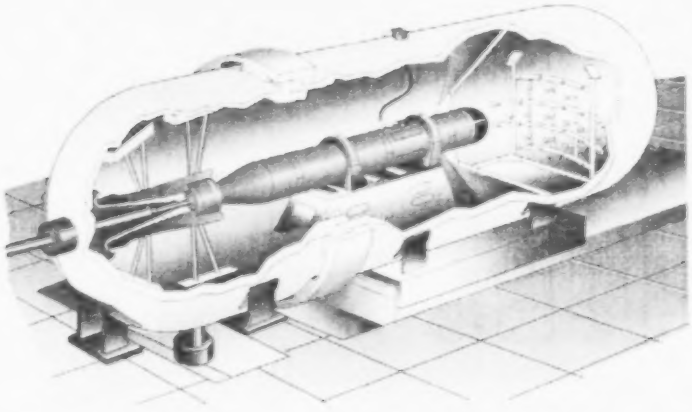

Figure 7. *Exterior and cutaway views of the UWEF pressure vessel.*

The test software produces a simulation of undersea conditions such as target and countermeasures echoes, flow noises and waterborne reverberation. It also possesses an extensive library of weapon/vehicle signatures and sound profiles. Responding to these acoustic stimuli, the weapon responds with its acoustic transmissions, engine speed changes and manoeuvring commands. The UWEF then provides appropriate "motion" feedback.

An innovative arrangement of acoustic absorbers and isolators within the pressure vessel controls background noises and reverberations, thus acoustically "removing" the steel vessel itself from the sound environment. Another essential pressure vessel component is a unique hydrodynamic propulsion load simulator that surrounds the test vehicle's propulsion components (including propellers or propulsor nozzles and rudders or fins) to control and measure water flow through the propulsor.

Contact: Charles Thurman, Supervising Engineer, Undersea Weapon Evaluation Facility, Keyport, Washington, 98345, (306) 396-2318 thurmc@kpt.nuwc.navy.mil or Robert D. Marciniak, Applied Research Laboratory, Penn State University, State College, Pa, 16802, rxm16@psu.edu

7.1.2 ASTS

The following are excerpts from a report by Robert Marciniak[75] concerning the ASTS (Acoustic Simulation Test System).

The Applied Research Laboratory at Penn State University (ARL) has created a torpedo Acoustic Stimulation Test System (ASTS). It is a land-based acoustic/electronic evaluation system for a torpedo sonar/guidance system operating in a water-filled acoustic tank. The system tests all major functions of an operational torpedo sonar/guidance system in a closed-loop condition within a controllable environment. The acoustic stimulation is accomplished by computer-driven arrays of specially designed acoustic transducers located in front of the torpedo nose section. The control system consists of a very-high-speed parallel digital signal processor (DSP), associated analog system pre-conditioning circuitry, and the acoustic projectors/receivers. Commercial signal processors form the core of signal processing.

The acoustic input to the system is the torpedo's sonar transmit pulse sensed by the acoustic receive array (transmit monitors). The stimulator uses the spatial, spectral, and temporal characteristics of the sonar transmit pulse along with active target and reverberation-generating algorithms, and includes the effects of torpedo velocity, transmit offset angle, transmit source level, torpedo velocity changes after transmit, and target characteristics. The acoustic output of the ASTS contains composite contributions of all targets, both passive and active, and reverberations (volume, surface, bottom), including the effects of velocity, acoustic level, and spatial characteristics of the targets, along with realistic reverberation returns, Doppler-shifted and positioned according to the transmit direction. There are also special functions to compensate for the mismatches in the signal and acoustic paths on the acoustic stimulation system. The source for interference signals or false targets such as both broad and narrow band countermeasures (BBCM and NBCM), are generated externally. The generation of torpedo flow noise is accomplished by the introduction of uncorrelated acoustic noise in the nearfield of the torpedo sonar system transducer by the noise ring transducers.

The level of the uncorrelated noise can be programmed to correspond to the expected total self-noise of the torpedo. The system produces water-borne acoustic signals, which stimulate the torpedo's sonar array and guidance system.

Although the system is capable of operation as low as 15000 Hz, it has not been used there before. Regarding acoustic models, the ASTS is not associated with any particular model. Spatial characteristics are controlled by the unit's-under-test (UUT) steered beam, or beams, as well as the physical aperture of the ASTS array itself. Temporal characteristics are dictated by trajectories of both the UUT and target, the acoustic cycles of the UUT and ASTS system controller event-timing. Frequency information is a function of input to ASTS from the UUT and target profile, as well as the operating frequency range of the ASTS system itself. Lastly, reverberation and target-return models are implemented by user-supplied weighting coefficients. Generally speaking, at any instant in time the reverberation and/or target return output is a weighted sum of samples using the programmed weights and the UUT's buffered, doppler-corrected transmit signal.

Contact: Robert D. Marciniak, Applied Research Laboratory, Penn State University, State College, Pa, 16802, rxm16@psu.edu

7.1.3 WAF

The following are excerpts from an article by Donald Katyl[76] about the WAF (Weapons Analysis Facility).

The WAF is the Navy's premier hardware-in-the-loop torpedo simulation lab begun in 1987 to support developmental testing of the Mk48 Advanced Capability (ADCAP) torpedoes. Since then it has matured into a full spectrum undersea weapons developmental and operational testing, training, and tactics development environment and now includes simulators for all U.S. heavyweight and lightweight torpedoes. The WAF's role in the Synthetic Environment Tactical Integration (SETI) project involves "firing" a weapon simulator in the WAF for a submarine on a test range. Shipboard systems extract weapon launch codes from the fire control system and send them through the water via an underwater acoustic modem to the range tracking system. A shore-based system in West Palm Beach, Florida takes these codes and sends them to the WAF in Newport, Rhode Island. The data then travel by satellite link to the test range in the Caribbean Sea.

BBN Technologies writes the following paragraph in their "What we do: \modeling, simulation, & training\" web page with link: http://www.bbn.com/mst/waf.html "The Weapons Analysis Facility (WAF) is a large, real-time multi-processor system for undersea warfare simulation. The simulation-stimulation system provides a synthetic environment, or virtual reality, for torpedoes and related systems. In the WAF laboratory, torpedo processors behave as if they were operating at a specified site on the globe and confronting a specified set of targets. The WAF provides acquisition support for the U.S. Navy by predicting performance and verifying software and also aids in training. The U.S. Department of Defence has declared the project a national asset."

Will Canto[77] describes the entire test system, including information about the test range AUTEC, the SETI and the communication centre. On the topic of the WAF, he writes "The actual Mk 48 ADCAP torpedo guidance and control hardware and its embedded

software reside at the WAF and constitute an OPTEVFOR-certified simulation. A nearby supercomputer simulates the torpedo-target geometry and the underwater acoustic environment, and generates a high fidelity representation of what the torpedo would "hear" at every moment of the evolving scenario. These acoustic inputs stimulate the torpedo guidance system on the bench, which interprets the data and responds with steering commands. These, in turn, are fed back to the computer simulation to move the scenario forward in time."

Ernest Correia[78] writes about the data presentations of the WAF, saying "The detailed representations of acoustic environment, target and weapon functional operation can produce up to two gigabytes of data for a single simulated weapon run. To enable the rapid and ready access to desired data products, the WAF takes advantage of a number of tailored graphic and pictorial display formats. In addition, the facility has available extremely flexible WAF-unique analysis software tools and applications to generate detailed data presentations such as spectral plots, histograms, crosscorrelation and autocorrelation diagrams, and geographic/time plots."

Contact: Tom Haley, Undersea Simulation and Analysis, Naval Undersea Warfare Center, 1176 Howell Street, Newport, RI 02878, (401) 832-3223, HaleyTB@Npt.NUWC.Navy.Mil. Mr Haley suggests that if more information is desired, we should take steps to establish a technical exchange meeting through formal channels.

7.1.4 Opinions On Stimulation Facilities

These three major facilities are interesting but probably not relevant because they are all concerned with stimulating torpedoes at frequencies well above the target range for this report. Also, none of the facilities appear to have separable stimulation software that could be adapted to a lower frequency range.

7.2 Sonar Stimulator Models

Henry (Chic) Weinberg, NUWC, the creator of CASS/GRAB, emailed a response to my question about models used in sonar stimulators. He said "I still have very strong opinions on the subject. For example, almost all the computer power in stimulators goes into targets at the expense of the environment. This forces the prop loss people to make certain compromises like limiting multipath arrivals. They always select the strongest eigenrays and throw away the others. One of the many difficulties with this is that when you pass from one bottom bounce region to another, the strongest eigenrays change. This leads to some interesting displays that have been named holes in the ocean, picket fences, and my favourite, the zipper." I note that none of the stimulation models described below mention anything about this self-imposed limitation, so I assume they all suffer in silence.

7.2.1 SST

The Sonar Simulation Toolset SST is a stimulator created by Robert Goddard from the Applied Physics Laboratory who has communicated by email. Its primary output is a stochastic multi-channel time series representing the signal on a set of wires, either behind the transducers (element level) or behind the beamformer (beam level). Those signals are suitable for listening or (more often) for feeding into the signal processing stage of the sonar receiver or a computer model. The reverberation calculations are not those of CASS, but are the creation of SST. (See reference 13) SST can be used throughout the frequency range of

interest here, with some caveats. The underlying sound propagation models are GRAB, FAME or isovelocity, which are based on eigenrays, so the accuracy decreases below a few kHz. Goddard mentions in his Questionnaire responses (Section 7.3.1) that he feels the lack of bottom layering is one of the factors that impose a low frequency limit.

About a decade ago SST was exported to DREA as part of a military-to-military agreement. More recently, it was exported to SACLANTCEN. To obtain an updated copy for DRDC, contact ONR Code 333, Adam Nucci, nucciaj@ONR.Navy.Mil, 703-696-7255. Robert Goddard writes that he is in the final throes of editing a major paper about SST for the U. S. Navy Journal of Underwater Acoustics. The journal is classified Secret, however his article is unclassified but restricted to US DoD or DoD contractors. Again, Adam Nucci is the contact for release permission.

Contact: Robert P. Goddard, Senior Physicist, Applied Physics Laboratory, University of Washington, 1013 NE 40th St., Seattle, WA 98105-6698, 206-543-1267; FAX 206-543-6785; cell 206-718-4417, Robert_Goddard@apl.washington.edu

7.2.2 AWESIM

Speaking about AWESIM (All World Environmental Simulation), William Beatty, communicating via email, says, "We are stimulating the sonar system at the element level of all sensors and are using an "off-the-shelf" tactical ARCI sonar system. AWESIM is now mature and is producing incredible results. Effects you never have seen before in simulators show up correctly. It helps to get the physics right. CASS/GRAB is active model."

Rick Krutz writes "AWESIM was developed with passive sonar as the priority. We placed an emphasis on the quality of target data and have worked with ONI to create realistic acoustic signatures. The base signatures are also enhanced with the inclusion of transient data that can be injected with the raw target stream. The transients can be anything; and we have created complex biologic targets by injecting actual biologic sounds into the simulation. The sounds are just standard .wav files that have been re-sampled, filtered, edited, and level adjusted. Threat active emissions can be treated in the same way; allowing us to deal with very complex pulse types that would be hard to simulate. AWESIM manages up to 40 concurrent ray paths per target per sensor. This allows a high degree of fidelity in the quality of the simulation; reinforcement and cancellation effects occur as a natural part of the process."

"We are just beginning the process of including a monostatic active component in our simulation. Having CASS as the base model allows us a great deal of flexibility in our approach. As this effort solidifies we will know more about the issues that are probably of high importance to you. As I was trying to answer your questions for the Questionnaire response (in Section 7.3.2), I found myself referring to the CASS documentation a great deal. Chic Weinberg who is the primary developer of CASS and GRAB works as part of our team."

Contact: Rick Krutz, Engineering Program Director, Presearch Incorporated, NSWCCD, (301) 227-5269, rick.krutz@presearch.com and William F Beatty CRBE, Code 7306, NSWCCD, 301-227-5644 BeattyWF@nswccd.navy.mil

7.2.3 CANTASS, INSPIRE and ODIN

The Canadian company Array Systems Computing Inc. offers three models that have some form of stimulation capability: the CANTASS Mission Simulator Model, Inspire, and ODIN. Details about these models are offered in the Questionnaire response section, CANTASS in section 7.3.3, Inspire in section 7.3.4, and ODIN in section 7.3.5.

Gene Joelson, communicating via email, states, "Array has expertise in passive and active sonar signal processing. In particular, our current contract to provide the Royal Swedish Navy with a single system to process all underwater acoustic data collected by their passive and active sensors (on ocean bottom or operated by submarine, ship, and aircraft) includes both requirements. We are also providing a similar system to the German Navy."

"Regarding sonar stimulators, Array has provided a high fidelity stimulator as a subsystem in the CANTASS Mission Simulator (CMS). The CMS is in service in the Fleet Schools of Halifax and Esquimalt. The stimulator provides a high fidelity stream of synthetic data to the CMS signal processor. We continually pursue business globally with strategic teaming partners, and offer the Inspire and ODIN models in conjunction with our partners."

Contact: E.R. (Gene) Joelson, M.Sc., M.B.A., P.Eng., Director of Business Development, Array Systems Computing Inc., 1120 Finch Ave. West, 7th Floor, Toronto, Ontario, Canada M3J 3H7, Office: 416-736-0900 ext 282, Mobile: 416-434-2499, gjoelson@array.ca or web site: www.array.ca.

7.2.4 EVA Server

Bill Renner and Tony Eller, SAIC, communicating via email, returned a questionnaire describing the EVA Server. It uses ASTRAL as its propagation engine and is listed for the frequency range 50 Hz to 10 kHz. It has all the Navy Standard environmental models: ANDES for noise, Lambert's Law using the Mackenzie Coefficient for bottom scattering strength, Chapman and Harris surface scattering strength, and LFBL and HFBL bottom losses. The questionnaire response is in Section 7.3.6.

Contact: Bill Renner, SAIC, McLean, Virginia, WILLIAM.W.RENNER@saic.com

7.2.5 EPOCSS

Garry Brown, communicating via email, mentions the EPOCSS project. He says, "An older MOD sonar stimulation activity is the EPOCSS project. This was a near real-time Ada software project that used simulation truth platform positions to generate input suitable for MOD's CIRCE Sonar Processor. Resources for this were directed elsewhere and it has not been touched for many years. Source code is neat and available, but it was not packaged for distribution."

Contact: Garry Brown, Maritime Tactical Experimentation Group, DSTO MOD, Australia, +61 8 8259 7519 Garry.Brown@dsto.defence.gov.au

7.2.6 PAPS-II

My telephone conversation with Mr Marks was not informative and I was unable to learn more about this model. I include it here for completeness.

Contact: William Marks, Naval Air Weapons Center, Patuxent River, MD. (301) 342-2068, William.marks@navy.mil

7.2.7 Opinions on Stimulation Models

The SST model seems to be the most mature model in the sense that it has been around for a while, has been used extensively by the torpedo community, and has a great deal of documentation. I would list SST as the first choice for a stimulator model. I doubt that AWESIM would be obtainable because of its library of classified target data, and without that library, it's just CASS. On this side of the border, the models offered by the company Array Computing do not have high enough fidelity in the propagation and reverberation computations for mid to low frequency use in shallow water over complex sediments. CANTASS is a passive model with no range dependence. Inspire is set up for high-frequency use (employing APLUW environmental models) and has very simple propagation (20 log r). ODIN is also set up for high-frequency use and is not range dependent. The SAIC model EVA Server would not have very high fidelity as it uses ASTRAL for it's propagation and very outdated scattering strength models. I was unable to obtain any information on PAPS-II, and the Australians had little information to send me.

7.3 Questionnaire Responses

7.3.1 SST

Topic area	Response (Model name, physical approach or value)
Stimulation Model name and acronym	Sonar Simulation Toolset (SST)
Acoustic propagation and reverberation models employed	Propagation: CASS/GRAB, GSM/(MULTIP,FAME,...), straight-line (isovelocity) eigenrays. Reverberation: SST's own broadband, bistatic scattering function model feeds into a multi-channel Gaussian time series generation stage.
Frequency range of operation	Above a few kHz in shallow water, lower in deep water, depending on fidelity requirements
Maximum spatial ranges of application	None
Pulse types being modelled	Any. SST provides flexible means of generating signals. If those prove insufficient, you can provide external time series.
Beam patterns being modelled	Any. Many internal options, or tabulate by elevation, bearing, and frequency.
Bistatic geometry capability?	Yes. Everything is treated as bistatic. Monostatic geometry merely means the transmitter and receiver have the same trajectory.
Shallow water capability?	Yes
Range dependence in bathymetry and sound speed profile?	Bathymetry can depend on location (with CASS/GRAB propagation model). Currently sound speed cannot, but CASS/GRAB allows it so it would be easy to add.
Range dependence capability maintained in reverberation model?	Yes. Surface and bottom characteristics, as well as bathymetry, can depend on location.
Reverberation model beam pattern - Side lobe capability? - Broadband capability?	Yes, yes
Bottom Loss model - Using bottom-layering information? - Frequency transitions needed?	No bottom layering. This is one of the factors that impose a low-frequency limit. Re transitions: If I understand this question, I think not. The Jackson bottom model is valid over the entire frequency range, down to where layering becomes important. However, the surface model does have a transition; SST has separate high-frequency and

	mid-low frequency models. I would love to mesh them together, but I haven't found bistatic data in the transition region.
Bottom Scattering Strength model - High angle term? - Volume term?	Yes, yes
Surface Scattering Strength - Bubble contribution? - Spectral spread term?	Yes, yes
Volume Scattering Strength model - Shallow water day/night model?	User must do this explicitly. Specify any number of scattering layers with user-specified depth ranges and strengths.
Ambient Noise model - Environmental? - Shipping?	No. SST can generate Gaussian noise with user-specified power spectra and channel-channel cross-spectra, but those spectra must be computed externally.
Target Strength model	Broadband, multi-highlight, plus provision for getting highlights from an external TS model.
Target kinematics?	User specifies arbitrary trajectories for transmitter, receiver, and target. Issues of control or physical realism of trajectories are not addressed by SST.
Fluctuation statistics for each component of reverberation and noise?	Reverberation is Gaussian, noise is Gaussian plus harmonic tone families if generated internally. Arbitrary externally-generated noise may be added. We are currently funded to generalize reverberation statistics.
Specular coherence?	We are partway there, with time and frequency spreading based on near-specular roughness model for surface and bottom reflections. I am currently writing a paper on this.
Any hybrid combinations of measured data and model calculations?	Yes. External time series can be used as transmitted signal, noise emitted by a target/CM/etc, or added to final time series as ambient or self noise.
Output displays and analysis tools	SST contains some signal processing tools (e.g. spectral analysis) but no displays. A large and growing set of Matlab scripts for analysis and display are distributed with SST.
Validation efforts	Spotty. Several studies including comparison to field data have been done, and I am actively seeking good data. Funding is always difficult for validation. The component models are based on data, and we always make sure SST

	correctly implements and integrates the models, but that's too indirect to be called validation.
Personal opinions concerning the models chosen	GRAB is pretty good as a general propagation model, but the CASS software is difficult to work with. I wish I had a good range-dependent propagation model with a modern implementation. I would like to extend SST to lower frequencies using non-eigenray propagation models and layered bottom models, but that would require more funding than I have. The surface and bottom models are not the very latest ones, even for mid to high frequencies; I plan to remedy that this year, at least in part. SST's own models for reverberation, passive reception, target echo generation, beam patterns, etc. are the best and most flexible available anywhere, and getting better. SST is a very general object-oriented framework that ties together a large number of component models, with the single purpose of generating realistic received time series. Adding a new alternative for any of the component models is relatively easy. Current major thrusts: Improve coherence model for forward reflection; model non-Gaussian target-like clutter; improve speed; make it "open" for sub-model sharing and for use as a "time series server" component of a higher-level simulation.
Most difficult aspect of modelling	Always validation. Existing data rarely include all of the information necessary for validation, and funding for experiments focused on validation is hard to find.
Availability	Available to US DoD or DoD contractors only. Others require authorization from ONR Code 333. (Some foreign transfers have been approved.)
Documentation	Extensive. "SST Web" is a large HTML web covering how to use SST. Physics and math are

	documented in an article submitted to U. S. Navy Journal of Underwater Acoustics (Secret journal, unclassified but restricted article). A more detailed version of that article is provided with SST as a technical report.

7.3.2 AWESIM

Topic Area	Response (Model name, physical approach or value)
Stimulation Model name and acronym	All World Environment Simulator (AWESIM)
Acoustic propagation and reverberation models employed	CASS/GRAB for TL, CASS for reverb
Frequency range of operation	LF, MF, HF
Maximum spatial ranges of application	Environment specific
Pulse types being modelled	CW, FM, other
Beam patterns being modelled	N/A; element level simulation
Bistatic geometry capability?	Yes
Shallow water capability?	Yes
Range dependence in bathymetry and sound speed profile?	Yes
Range dependence capability maintained in reverberation model?	Yes
Reverberation model beam pattern - Side lobe capability? - Broadband capability?	CASS post-processes the eigenrays to include source level and beam pattern effects for transmission loss calculations and/or to include backscattering effects to compute reverberation.
Bottom Loss model - Using bottom-layering information? - Frequency transitions needed?	LFBL, HFBL. Layering information is used. Frequency transitions needed between LFBL and HFBL.
Bottom Scattering Strength model - High angle term? - Volume term?	Table driven with some built-in models (Mackenzi, APL/UW, Mid-Frequency. It does deal with high angle terms and at least one of the built in models has a volume term.
Surface Scattering Strength - Bubble contribution? - Spectral spread term?	Table driven with some built-in models (Chapman-Harris, APL/UW, Mid-Frequency). Bubble-effects accounted for in CASS.
Volume Scattering Strength model - Shallow water day/night model?	Table driven with many built-in models (re: CASS design documentation). Day/night not documented if it is in there.
Ambient Noise model - Environmental? - Shipping?	Currently use ANDES; Transitioning to DANM Both combine environmental and shipping data
Target kinematics?	Based on ONI operational data
Fluctuation statistics for each component of reverberation and noise?	Noise outputs allowed to vary (predicted noise used as the mean of Gaussian distribution, variance is a simulation input).
Specular coherence?	If specular coherence refers to "…scattering

	cross-section intensity due to large-scale wave facets according to the specular point theory", then it is dealt with in CASS. If it is not, then I am unsure what is meant here.
Any hybrid combinations of measured data and model calculations?	Noise is a combination of measured sensor data and historical background noise
Output displays and analysis tools	Connected to various versions of the BQQ-10 sonar
Validation efforts	Qualitative assessment by ONI
Personal opinions concerning the models chosen	AWESIM is designed to allow model replacement as higher fidelity models become available or more computationally allowable.
Most difficult aspect of modelling	Real-time performance of system requires coordinated operation of 700+ processor Linux cluster.

7.3.3 CANTASS (Passive)

Topic Area	Response (Model name, physical approach or value)
Stimulation Model name and acronym	CANTASS Mission Simulator Model
Acoustic propagation and reverberation models employed	Ray Path for Acoustic Propagation. Model is passive.
Frequency range of operation	0 Hz – 10 kHz (Lower frequency limit is for ray path model, upper frequency limit is due to computational complexity).
Maximum spatial ranges of application	512 nmi x 512 nmi
Pulse types being modelled	None
Beam patterns being modelled	Yes
Bistatic geometry capability?	No.
Shallow water capability?	No.
Range dependence in bathymetry and sound speed profile?	No
Range dependence capability maintained in reverberation model?	Not Applicable
Reverberation model beam pattern - Side lobe capability? - Broadband capability?	Not Applicable
Bottom Loss model - Using bottom-layering information? - Frequency transitions needed?	User can specify bottom characteristic as a single layer.
Bottom Scattering Strength model - High angle term? - Volume term?	Not Applicable
Surface Scattering Strength - Bubble contribution? - Spectral spread term?	Not Applicable
Volume Scattering Strength model - Shallow water day/night model?	Not Applicable
Ambient Noise model - Environmental? - Shipping?	Ambient Noise and Shipping values can be selected from a predefined list. The Operators can also define their own curves, if desired. Vertical and Horizontal directionality is also accounted for.
Target Strength model	Not Applicable
Target kinematics?	Yes. Operator can specify motion through way points, and the rate of change.
Fluctuation statistics for each component of reverberation and noise?	Yes, time dependent fluctuations can be incorporated into the scenario

Specular coherence?	No
Any hybrid combinations of measured data and model calculations?	No
Output displays and analysis tools	Lofar, Demon, Time/Frequency Representations, , Tactical.
Validation efforts	Propagation Model is from the US Navy and in use by the Canadian Navy.
Personal opinions concerning the models chosen	Model can be expanded to handle range dependent environments fairly easily.
Most difficult aspect of modelling	

7.3.4 Inspire

Topic Area	Response (Model name, physical approach or value)
Stimulation Model name and acronym	Inspire
Acoustic propagation and reverberation models employed	Uses a Snell's law raytrace and either spherical spreading or a ray separation technique to calculate propagation loss throughout the water column. There are multiple models encoded for scattering from surfaces or in the volume. The full range of models and techniques employed within Inspire can be seen in the attached table.
Frequency range of operation	Typically used in the frequency range of 10 kHz to 450 kHz, however the validity of the models has been stretched to lower and higher frequencies
Maximum spatial ranges of application	Not found – increased range and depth can affect run times, but no physical limit has yet been reached
Pulse types being modelled	CW and FM
Beam patterns being modelled	Horizontal and vertical. Beam patterns can be calculated from array length or element geometry or input as tables.
Bistatic geometry capability?	No, but should be possible to expend to do this.
Shallow water capability?	Yes. Currently used for MCM applications.
Range dependence in bathymetry and sound speed profile?	Under development, also range dependence in seabed type.
Range dependence capability maintained in reverberation model?	Under development
Reverberation model beam pattern - Side lobe capability? - Broadband capability?	Targets can be placed off axis in the side lobes or any other part of the beam pattern as desired. Broadband can be modelled using sub-banding.
Bottom Loss model - Using bottom-layering information? - Frequency transitions needed?	Available models are identified in the attached table. Could be extended to include other models
Bottom Scattering Strength model - High angle term? - Volume term?	Available models are identified in the attached table. Could be extended to include other models High angle term is inherent to APL-UW 9407 and Ellis and Crowe models Volume term is inherent to APL-UW 9407

	model
Surface Scattering Strength	Yes
- Bubble contribution?	Bubble contribution is inherent to APL-UW 9407 model
- Spectral spread term?	No spectral spreading modelled
Volume Scattering Strength model	Yes
- Shallow water day/night model?	No day/night model, although the user can select the marine life density appropriate to the time of day.
Ambient Noise model	Yes; environmental noise but no specific shipping noise model
- Environmental?	
- Shipping?	
Target Strength model	Point source target strength. Target strength modelling capability exists elsewhere in QinetiQ.
Target kinematics?	No
Fluctuation statistics for each component of reverberation and noise?	Under development (Rayleigh and K-law)
Specular coherence?	No
Any hybrid combinations of measured data and model calculations?	No
Output displays and analysis tools	Yes – comprehensive GUI and display routines
Validation efforts	Inspire is developed under high control MOD software guidelines and has thus been very rigorously subjected to V&V processes.
Personal opinions concerning the models chosen	Inspire is easy to install and use and has been tightly controlled throughout the development process. Additional environmental scattering and noise models can be incorporated if desired.
Most difficult aspect of modelling	

Additional information about Inspire

	Model Group	Model / Technique	Date of validation
Inspire	Raytrace	Isovelocity	22/05/03
		Snell's law raytrace	22/05/03
	Propagation loss	10 log r^2	22/05/03
		Ray separation	22/05/03
	Speed of sound	Chen-Millero-Li	05/08/03
		Del Grosso	05/08/03
		Mackenzie	05/08/03
	Multi paths		02/10/03
	Coherent processing	Sub-bands	02/10/03
	Target seabed interaction		02/10/03

Environmental models	Blanking range		In issue 1.4
	Absorption	Fisher-Simmons	21/05/03
		Schulkin & Marsh	21/05/03
		Thorp	20/05/03
		Francois-Garrison	20/05/03
	Sea surface reverberation	LF Chapman & Harris	05/08/03
		HF Chapman & Harris	05/08/03
		Perturbation	05/08/03
		Kirby	05/08/03
		APL-UW 9407	05/08/03
	Sea surface forward loss	APL-UW 9407	05/08/03
	Seabed reverberation	McKinney-Anderson	14/05/03
		Ellis & Crowe	14/05/03
		Lambert	15/05/03
		APL-UW 9407	15/05/03
		APL-UW 9407 Bistatic	28/05/03
	Seabed forward loss	APL-UW 9407	12/05/03
		APL-UW 9407 Bistatic	28/05/03
	Volume reverberation	SEARAY	03/10/03
		APL-UW 9407	03/10/03
	Bistatic reverberation approximation	Average angle	03/10/03
		Separable approximation	03/10/03
	Ambient noise	SEARAY	21/05/03
		MCS	21/05/03
		APL-UW 9407	In issue 1.4
Sonar representation	Beam patterns	Element-level data	03/10/03
		'Taylor' approximation	03/10/03
		Length to beamwidth	03/10/03
		Beam steering	In issue 1.4
	Scattering area		03/10/03
	Scattering volume		03/10/03

7.3.5 ODIN

Topic Area	Response (Model name, physical approach or value)
Stimulation Model name and acronym	ODIN
Acoustic propagation and reverberation models employed	Nereus (includes Bellhop ray-trace)
Frequency range of operation	500 Hz – 100 kHz
Maximum spatial ranges of application	100k +
Pulse types being modelled	CW, LFM, HFM, Costas, Noise, SFM, SinFM + others. Additional pulses types can be added.
Beam patterns being modelled	Yes, full horizontal and vertical
Bistatic geometry capability?	Yes
Shallow water capability?	Yes
Range dependence in bathymetry and sound speed profile?	No
Range dependence capability maintained in reverberation model?	No
Reverberation model beam pattern - Side lobe capability? - Broadband capability?	Yes, full beam patterns modeled. Broadband can be modeled using sub-banding.
Bottom Loss model - Using bottom-layering information? - Frequency transitions needed?	APLUW or user-defined tables. Alternatives could be included.
Bottom Scattering Strength model - High angle term? - Volume term?	APLUW or user-defined tables. Includes high-angle & volume components. Alternatives could be included.
Surface Scattering Strength - Bubble contribution? - Spectral spread term?	APLUW or user-defined tables. Includes bubble contribution and wave motion model for spectral spreading. Alternatives could be included.
Volume Scattering Strength model - Shallow water day/night model?	User-defined scattering strength. Day-night differences can be modeled using different inputs.
Ambient Noise model - Environmental? - Shipping?	Environmental noise model for greater thar. 1 kHz. Supports user-defined omni-directional shipping noise.
Target Strength model	3 methods: Aspect-dependent look up table of Peak and Integrated TS, aspect-dependent multiple highlight model, high fidelity target highlight model.
Target kinematics?	Yes for an arbitrary number of platforms
Fluctuation statistics for each component of	Yes – very short, short, medium term

reverberation and noise?	variability. Supports Gaussian, K-law and correlated K-law distributions.
Specular coherence?	User-specified
Any hybrid combinations of measured data and model calculations?	No, but could be extended to do this.
Output displays and analysis tools	Full graphics and displays supporting various levels of use, e.g. engagement, data processing, signal processing output.
Validation efforts	Validation and verification log book maintained. Propagation models verified against similar models. Validation of reverberation models against trials data.
Personal opinions concerning the models chosen	APLUW is international standard for acoustic submodels, and appropriate for 10 – 100kHz. The inclusion of other algorithms for surface and seabed interactions (which should be a straightforward process) should provide good performance in the 0.5 – 10 kHz frequency range.
Most difficult aspect of modelling	

7.3.6 EVA Server

Topic Area	Response (Model name, physical approach or value)
Stimulation Model name and acronym	EVA Server
Acoustic propagation and reverberation models employed	ASTRAL and ASPM
Frequency range of operation	50 – 10,000 Hz
Maximum spatial ranges of application	200 nm
Pulse types being modelled	CW and FM
Beam patterns being modelled	Vertical directionality handled by model; horizontal directionality must be applied by user
Bistatic geometry capability?	Yes
Shallow water capability?	No fixed limits (Accuracy may degrade in water depths less than approximately 10 wavelengths)
Range dependence in bathymetry and sound speed profile?	Yes
Range dependence capability maintained in reverberation model?	Yes
Reverberation model beam pattern - Side lobe capability? - Broadband capability?	Side lobe definition and broadband effects are implicit in user-supplied beam pattern
Bottom Loss model	LFBL and HFBL
- Using bottom-layering information?	Handled implicitly by LFBLTB
- Frequency transitions needed?	Frequency transitions can be problematic
Bottom Scattering Strength model	Lambert's Law (with MacKenzie coefficient)
- High angle term?	
- Volume term?	
Surface Scattering Strength	Modified Chapman/Harris
- Bubble contribution?	
- Spectral spread term?	
Volume Scattering Strength model	VSS Database
- Shallow water day/night model?	Binary day/night descriptors
Ambient Noise model	Based on ANDES.
- Environmental?	Environmental noise includes wind, rain, and localized rain showers
- Shipping?	Shipping noise includes temporal fluctuations due to the movement of random ships near the receiver
Target Strength model	Not modeled

Target kinematics?	Not modeled
Fluctuation statistics for each component of reverberation and noise?	Not modeled
Specular coherence?	Not modeled
Any hybrid combinations of measured data and model calculations?	No
Output displays and analysis tools	Limited
Validation efforts	Primarily limited to validation of underlying models (ASTRAL, ANDES and ASPM)
Personal opinions concerning the models chosen	Models were chosen to meet stringent execution time constraints imposed by realtime requirements of trainers.
Most difficult aspect of modelling	

7.4 Other Active Sonar Performance Models

Etter[3] in table 10.6 gives a summary of new or modified sonar performance models, with a précis about each one. These models are primarily used to predict active sonar signal excess and to evaluate multistatic deployments of sensors. The model IMAT also includes training modules. Of these active models, the following may be applicable to pulse propagation reconstruction.

7.4.1 SWAMI

In 1997, Theriault and Ellis[79] presented a description of a DRDC model for active sonar modelling called SWAMI (Shallow Water Active-sonar Modelling Initiative). This model computes propagation loss using PROLOS in an Nx2D manner to include azimuthal variability for beam pattern side lobe modelling. It is built around a flexible architecture so that some of the modelling elements, the surface, bottom or volume reverberation or noise, can be added directly from a measurement instead of being generated by a model. The current output of the model is signal excess, with intermediate outputs of reverberation available to the scientist. Being an 'in-house' model is a real advantage, because it should be possible to upgrade the model to provide a time series output.

7.4.2 BAM

The Naval Air Weapon Center, Patuxent River, MD (formerly Naval Air Development Center, Warminster, PA) has developed a bistatic acoustic model called BAM[80]. It predicts the performance of a sonar system by computing the echo-to-background ratios. It can model vertical line arrays, horizontal line arrays and volumetric arrays. It uses ray theory to compute the arrival time structure, adding the surface, bottom and volume reverberation time histories and the vertical distribution of ambient noise.

7.4.3 CASS

The system model CASS (Comprehensive Acoustic System Simulation)[81] evolved from the generic Sonar Model GSM, written by Henry (Chic) Weinberg in the 1980's. CASS offers choices for most sub-models but the preferred choice for propagation loss model is GRAB, a ray theory model that defines the frequency range of CASS as 600 Hz to 100 kHz. In CASS, all environmental inputs can have horizontal range dependence. All the calculated environmental parameters such as surface and bottom reflection coefficients and scattering strengths are range, azimuthal (Nx2D) and frequency dependent. And there are a variety of output products designed for use in the performance prediction of all sorts of sonar systems from towed arrays detections to mine hunting.

7.4.4 SUPREMO

The model SUPREMO[82] is a multistatic sonar performance model developed at SACLANT using the language Matlab. For propagation, it employs the ray theory models, and it calculates reflection coefficients for bottom loss using sediment and sub-bottom layering supporting compressional and shear propagation. It can use a range-dependent bathymetry but not the sound speed profile, and its range-dependent prop loss model, Brutus, produces range-averaged reverberation and intensity, meaning it removes phase information. SUPREMO offers the choice of bottom scattering strength equations from Lamberts Rule

with angles matching local bathymetry, omni, or angle independent. Surface scattering strength is Chapman-Harris. It can only model LFM pulses. The receiving arrays can be HLA's or circular planar arrays. The internal target strength model is based on the target dimensions, but is not described further. The reverberation statistical family is Rayleigh. There do not appear to be any pulse time series outputs, however if coherent propagation were available, it would not be hard to produce the required output since the programming language of SUPREMO is Matlab.

7.4.5 MODRAY

The MODRAY (Maritime Operations Division RAY tracer) underwater sound simulator[83] uses classical ray theory (meaning it locates the exact eigenrays that connect source and receiver) to propagate sound and it produces a time series at one or more receivers. It has no range dependence, it expects any "unevenness" to be modelled by defining surface and bottom scatterers, but it's not clear that this device would be very successful on slopes or canyons. Ambient noise due to distant shipping and wind/rain is modeled as coloured and far field. Signal types are CW or LFM, and Doppler shifts are computed for platform and array motions. Target strength is a user-defined dB reflectivity with azimuthal dependence. Run time is evidently an issue with MODRAY, as the users guide mentions that it is possible to use two-way interrupted propagation instead of "true" active propagation. This involves propagating the source signal to each target point, sampling the signal there, then propagating each of the samples to the receiver. There is a loss of accuracy depending on how sparse the samples are, but the simulation runs much faster.

7.4.6 Australian Federate

Garry Brown, communicating via email, says, "The MCS branch (SMCS and MTE groups), are currently working with a contractor to develop a medium fidelity track generating SONAR federate for the VMSA (HLA based). The intention of this federate is to replace all other SONAR federates in use by the MCS branch. It contains a configuration file that permits scalability from quite rudimentary SONAR parameters to reasonably complex (from a CS perspective) allowing complex beam patterns at user defined azimuth and elevation combinations, frequency bands, bearing rates, crossing contacts, integration, detection hold before track and track after loss. One of its limiting factors from a pure SONAR perspective is that it assumes beam pattern for a frequency band is constant. This version is an improvement over previous versions in the following respects:

- The array noise is not static and not isotropic.
- The environmental noise is not static and not isotropic.
- Beam patterns are complex.
- Quiet contacts can be masked depending upon SNR, frequency emissions, proximity to other contacts and beam pattern nulls.
- Collins arrays can be quite reasonably approximated.
- Beam level data is supplied to third party applications allowing LOFAR etc.
- Bearing rate effects holding a detection.
- Crossing contacts may be dropped.
- Ranging is possible depending upon configuration file settings, signal duty cycle etc."

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7.4.7 Opinions on Other Active Models

Not Recommended

The BAM model from NAWC is not a good choice because, unfortunately, the creator of this model, Dr. Charles Bartberger, has died, and there is no one at NAWC to replace him. The current status of the model is unknown. SUPREMO seems focused on low frequency propagation because of its elastic reflection coefficient ability, and the range-averaged output would not be suitable for time series construction. I don't know enough about its validation and documentation to recommend it. MODRAY is not range dependent and also has an unknown track record. The Australian Federate appears to be still under considerable development, and its application to stimulation is unclear.

Recommended

The DRDC in-house model SWAMI looks to be a promising candidate from which a stimulator could be built. If PROLOS is supplemented with the addition of a mid- to high-frequency ray theory propagation model, SWAMI could cover the entire frequency band 500 Hz to15000 kHz easily. One question may be the availability of documentation and efforts at validation.

The other obvious choice is CASS, which is used in the stimulator models SST and AWESIM. I note the developer of SST said in his questionnaire that he thinks the CASS software is difficult to work with. Those with experience with the 'old' GSM will understand those difficulties, and CASS is constructed in the same way. However, it is very well documented and validated.

8. Sources of Models

A few models are available on line on the Acoustical Society of America's web site for the Ocean Acoustics Library (http://oalib.saic.com). See Table 6 for a listing of models from this site. A further source of models is the U.S. Navy Oceanographic Office, Stennis Space Center, MS, who maintain a library of Navy-approved configuration-managed models and databases called the Oceanic and Atmospheric Master Library (OAML) models. Some of these models are classified however. To obtain OAML products, the point of contact is Lcdr Andy Cameron, DNDHQ, 613-996-5326, cameron.an@forces.gc.ca, the project officer for data exchange agreements for METOC between Canada and the US Navy. The contact person at Stennis is Mr. Walt Moskal, NAVOCEANO, N641, FAX DSN: 485-4569 or Commercial: (228) 688-4569, moskalw@navo.navy.mil.

Table 6. General propagation models available on the web

PHYSICAL APPROACH	MODEL NAME	CREATOR, INSTITUTION
Ray Theory, Ray tracing	BELLHOP	Porter, SAIC
	HARPO	Georges, NOAA
	Ray	Newhall, WHOI Pawlowicz, Univ. British Columbia
	Ray tracing for Tomography	Dushaw, APL/UW Colosi, WHOI
	TRIMAIN	Wright, NRL
Normal Modes	AW	Dzieciuch, Scripps
	COUPLE	Evans, SAIC
	Kracken	Porter, SAIC
	KrackenZ	Cristini, CNRS France
	MOATL	Ingenito, Wolf, NRL
	N Layer	Pedersen, Gordon, NOSC Hall, DSTO Australia
	WKBZ	Zhang, Chinese Academy of Sciences
Parabolic Equation	FOR 3D	Lee, NUWC
	MMPE, UMPE	Smith, Naval Post Graduate School Tappert, Rosenstiel School of Marine and Atmospheric Sciences
	PDPE	Avilov, Russia Inst
	PECAN	Brooke, DRDC Atlantic
	RAM	Collins, NRL
Wavenumber Integration	OASES	Schmidt, MIT
	RPRESS	Jvansson, Swedish Def. Res. Agency
	SPARC, SCOOTER	Porter, SAIC

9. Summary

This report summarizes the component models and approaches for active sonar modelling and waveform time series propagation. Existing sonar stimulator models and facilities were described. Recommendations were made on the maturity and practicality of the modelling in reverberation, ambient noise, propagation, environmental models, source models, fluctuation statistics, spatial and temporal coherence, spreading functions and target strength.

Component models

Propagation models for active prediction were surveyed. GRAB and PROLOS top the list for propagation model choices. New developments in component environmental models within the last 10 years include scattering strength theories for sediment roughness, sediment volume inhomogeneities, and surface wave bubble cloud scatter. A new formulation of ray theory has been applied to layered bottom propagation and the temporal spreading produced in the time series adds significantly to pulse spreading. Finally, new data confirm the statistical distributions of sediment reverberation are significantly non-Gaussian.

Component model shortcomings include the lack of a seamless bottom loss across the entire frequency range (currently there are three separate models to transition), the lack of target strength models for the upper end of the frequency range, and the lack of input information to supply the newest sediment models.

Stimulation facilities

Specially constructed research facilities devoted to testing underwater vehicles by stimulation were surveyed and, as one might expect, they are all hardware oriented and invest their acoustic resources primarily on target modelling.

Existing stimulator models

Several existing stimulation software packages were surveyed and they all seem designed to perform at mid to high frequency or in deep water because they all employ conventional ray theory for their propagation calculations. The leading candidate stimulation model is SST because of its versatility and availability, however it is presently designed for high frequency applications.

Some capabilities common among stimulation models are the offering of a full range of beam patterns and pulse types, the ability to include range dependence in bathymetry, and the capability to handle bistatic geometries.

Some deficiencies common to all stimulator models are the use of older scattering strength models, the neglect of the temporal structure of bottom layering reflections, and the application of Gaussian statistics for all fluctuations. All these deficiencies can be traced directly to the lack of input information to support the newest models and statistical distributions. To address these deficiencies, all of the stimulation models permit user-supplied tables as inputs.

Active propagation and system performance models

Active models were surveyed and the model deemed most adaptable to the construction of a stimulation model was CASS due to its extensive documentation and broad choice of components and capabilities. It has wide usage among the Naval community and is currently employed in two of the existing stimulators, SST and AWESIM. However, CASS uses a ray model for propagation and therefore is not the best choice for shallow water, low frequency application. The model SWAMI also received a tentative recommendation for the lower frequency operations.

Conclusions

There do not appear to be any existing models that would fully satisfy the requirements for computing time series for shallow water, low frequency operation as well as frequencies up to 15,000 Hz. However, the leading candidate stimulator, SST could be combined with the propagation model PROLOS to broaden its capabilities beyond ray theory for ducted and boundary-limited propagation.

The most important physical effects that are not currently modelled adequately in any of the models surveyed are the fluctuation statistics of bottom reverberation and temporal spread functions from bottom penetration. Both of these effects are crucial to accurately describe the pulse distortion and masking in a shallow water bottom limited environment.

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14. ABSTRACT

(U) This report summarizes the component models and approaches for active sonar modelling and waveform time series propagation. Existing sonar stimulator models and facilities are described. Recommendations are made on the maturity and practicality of the modelling in reverberation, ambient noise, propagation, environmental models, source models, fluctuation statistics, spatial and temporal coherence, spreading functions and target strength.

(U) Ce rapport résume les résultats d'une étude de sources documentaires ouvertes portant sur les modèles composants nécessaires et les approches existantes pour la modélisation de sonars actifs et la propagation de formes d'onde en série chronologique. Des installations et modèles de stimulateurs de sonar actuels sont décrits. Des recommandations sont présentées en ce qui concerne l'exploitabilité et la valeur pratique, pour le domaine d'intérêt visé, des techniques de modélisation de la réverbération, du bruit ambiant, de la propagation, des modèles environnementaux, des modèles de source, des statistiques sur les fluctuations, de la cohérence spatiale et temporelle, des fonctions d'étalement et de l'intensité de cible.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) Sonar Modelling
Active Sonar
Stimulators